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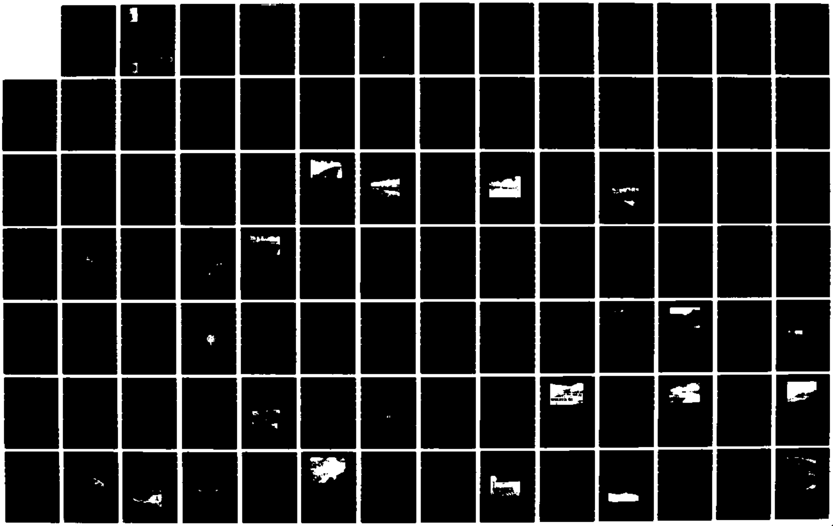

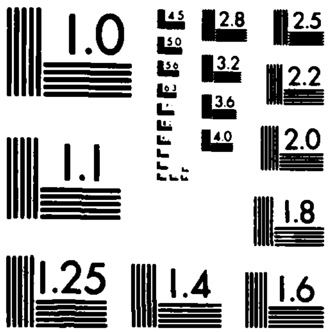
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ENVIRONMENTAL AND WATER QUALITY OPERATIONAL STUDIES

TECHNICAL REPORT E-84-11

ENVIRONMENTAL FEATURES FOR STREAMBANK PROTECTION PROJECTS

by

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This report provides guidance for incorporating environmental considerations into streambank protection projects. The stability of the streambanks of a channel is related to both site-specific and basinwide stream reach factors. Streambank erosion or failure is a natural fluvial process that is often accelerated by changes in geotechnical or hydraulic factors and especially the activities of man, e.g., reservoir construction or land use changes. Streambank protection projects stabilize the streambank,

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preventing or stopping erosion. Stabilization results in a range of environmental changes.

An information review was performed to identify environmental features for streambank protection projects. Environmental features are those planning, design, construction, and maintenance procedures or practices that minimize adverse environmental impacts or enhance terrestrial and aquatic habitats and the aesthetic quality of land and water associated with streambank protection projects. Such features include structural and nonstructural designs; construction procedures that are environmentally compatible; maintenance procedures; and institutional, planning, and management approaches for streambank protection projects.

Each feature is discussed in terms of concept, the purpose or appropriate use of the feature, environmental considerations, limitations to use of the feature, performance history, and cost.

PREFACE

The study described in this report was conducted as part of the Environmental and Water Quality Operational Studies (EWQOS) Program, Task VIB, *Design and Construction Techniques for Waterway Projects*. The EWQOS Program is sponsored by the Office, Chief of Engineers, US Army (OCE), and is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). The OCE Technical Monitors for EWQOS were Dr. John Bushman, Mr. Earl Eiker, and Mr. James L. Gottesman.

The study was conducted by Mr. Jim E. Henderson, on assignment to the Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), EL, and Mr. F. Douglas Shields, Jr., WREG. The work was conducted under the direct supervision of Mr. Michael R. Palermo, Chief, WREG, and under the general supervision of Mr. A. J. Green, Chief, EED, and Dr. John Harrison, Chief, EL. Program Manager of EWQOS was Dr. J. L. Mahloch, EL.

Commander and Director of WES during the study was COL Tilford C. Creel, CE. The Technical Director was Mr. F. R. Brown.

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CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.873	square metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
gallons (US liquid)	3.785412	cubic decimetres
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres
square miles	2.589998	square kilometres
tons (2000 lb, mass)	907.1847	kilograms

ENVIRONMENTAL FEATURES FOR STREAMBANK PROTECTION PROJECTS

PART I: INTRODUCTION

Background

1. The Corps of Engineers (CE) is committed to implementing the National Environmental Policy Act (NEPA) and other environmental statutes, regulations, and executive orders. The CE has issued several documents that contain general environmental guidelines and policies pertaining to the design and construction of water resource projects, and a review of these is presented by Shields and Palermo (1982). Specific design guidance to implement these guidelines and policies is still needed. The CE is currently conducting a large-scale, multiyear research program, the Environmental and Water Quality Operational Studies (EWQOS), to address high-priority environmental problems. Part of this program (Work Unit VIB) is aimed at providing environmental design and construction guidance for specific types of waterway projects. This guidance will assist CE field offices in implementing Federal and CE environmental policies.

2. Environmental guidelines for four main types of projects have been assembled under EWQOS Work Unit VIB: flood control channels (Shields 1982, Nunnally and Shields 1984), levees (Hynson et al. 1984), river training dikes (Burch et al. 1984) and streambank protection. Background information concerning the environmental problems of waterway projects is available from Thackston and Sneed (1982) and Shields and Palermo (1982). These categories were set up in a somewhat arbitrary fashion to facilitate information collection and review, and there is some overlap. Thackston and Sneed (1982), Shields and Palermo (1982), and Nunnally and Shields (1984) all contain limited information on environmental aspects of bank protection.

3. The CE recently completed an extensive program of research and demonstration in the area of streambank erosion control. The Section 32

Program documentation (Office, Chief of Engineers (OCE) 1978 and 1981) is a major source of information on causes of streambank erosion and methods of streambank protection. However, investigation of environmental aspects was not authorized under the Section 32 Program, and little environmental information can be gleaned from the documentation. The Section 32 Program reports do provide information on streambank failure and methods for streambank protection, which was used extensively in preparation of Parts II and III of this report. In addition, many of the environmental features presented in Parts IV and V were demonstrated during the Section 32 Program because they held potential as economic approaches to solving specific types of bank erosion problems. These features are identified in this report because they are beneficial from an aesthetic, recreational, or ecologic standpoint.

Purpose

4. The purpose of this report is to provide CE personnel with guidance on environmental considerations in design, construction, and maintenance of streambank protection projects. Detailed engineering information for the Section 32 projects is contained in the Section 32 Program documentation (OCE 1981). Detailed guidance for design of streambank protection projects is given in a draft Engineer Technical Letter "Streambank and Streambed Protection." This document provides supporting information for the environmental Engineer Manuals on Shallow Draft Waterways and Flood Control Channels.

Scope

5. This report deals with environmental aspects of streambank protection works on all sizes of streams and waterways. Coastal protection is not addressed, although some transfer of information may be possible. Streambank erosion processes and streambank protection methods are discussed briefly in Parts I-III, and available information regarding environmental effects is reviewed. Information contained in this report

was obtained from literature review, interviews, and case studies of specific projects. Streambank protection features were identified that minimize environmental impacts or enhance terrestrial and aquatic habitats, aesthetics, and recreation. Desirable environmental effects result from specific project designs or from construction, management, or maintenance practices. Structural designs are discussed in Part IV. Construction practices for proposed designs and procedures for management and maintenance of existing structures are contained in Part V. The feasibility and effectiveness of a given environmental feature were found to be influenced strongly by its physical and institutional environment. Accordingly, background information for several of the environmental features described in Parts IV and V is provided in Appendix A.

PART II: STREAMBANK FAILURE

6. Since there are several different types of streambank failure, streambank protection design requires a knowledge of the types of failure at the project site. Accordingly, the feasibility of environmental features and design modifications is determined by the dominant failure mechanisms. This part of the report provides information on streambank failure processes as background for the discussions of streambank protection methods, environmental effects, and environmental features which follow.

7. Streambank failure is the result of several physical processes working singly or in combination. In general, these processes may be classified as surface phenomena, such as the erosive removal of soil particles from the bank by streamflow, or subsurface phenomena, such as collapse of a saturated bank following a rapid drop in water level. Surface and subsurface phenomena are usually interrelated. For example, erosion of the bank toe (a surface phenomenon) would steepen the bank and might facilitate failure of the saturated bank as described above.

8. Streambank *erosion* is a continuously occurring phenomenon and is a natural process that may be accelerated or decelerated by human activities. However, for most streams, the vast majority of bank erosion occurs during and just after high flows. Simons, Li, and Associates (1982) estimate that 90 percent of all morphologic changes in rivers occur during only 5 to 10 percent of the time (during large flows). Erosive forces during floods and high flows may be one to two orders of magnitude greater than for normal flows.

9. Streams naturally erode their beds and banks and deposit the resulting sediments. However, over the time scale of interest to the engineer, natural streams tend toward a state of "quasi-equilibrium" in which erosion at one location is balanced by deposition at another (OCE 1981, Appendix C). Mean dimensions of a stable stream are fairly constant throughout a given reach. However, if human activities or natural events alter the dominant factors that control channel form (streamflow, sediment supply, and sediment characteristics), then accelerated or

unexpected erosion will result as the fluvial system forms a new quasi-equilibrium channel (OCE 1981, Appendix C).

10. Excellent qualitative discussions of the causes of streambank erosion are given in the Section 32 Program Main Report and Appendix C (OCE 1981) and Simons, Li and Associates (1982); additional information is available from Keown et al. (1977). River meandering and associated natural erosion are discussed by Leopold, Wolman, and Miller (1964), Vanoni (1975), and Klingeman and Bradley (1976). No attempt is made in this report to supplement or replace these references. Rather, the reader requiring more information is referred to these documents.

Natural Erosion

11. The term "natural streambank erosion" as used herein refers to processes which occur in the absence of significant human activities in the drainage basin or catastrophic natural events such as volcanic eruptions or forest fires. All streams erode their banks to some extent, and the diversity of physical conditions created by undercut banks, bar formation, and channel migration provides a diversity of habitats for fish and wildlife and a visual diversity that is often aesthetically pleasing.

Basin or reach scale

12. When streambank erosion is considered on a basinwide or long-reach scale, a crude balance or quasi-equilibrium is evident. The existence of such an equilibrium is due to the relationships between average water and sediment discharge and morphological variables. These relationships may be expressed as proportionalities (Smith and Patrick 1979):

- a. Depth of flow Y is directly related to water discharge Q.
- b. Channel width W is directly related to both Q and sediment discharge Q_s.
- c. Channel shape, expressed as width-to-depth ratio W/Y is directly related to Q_s.
- d. Channel slope is inversely related to Q and directly proportional to Q_s and median sediment grain size D_{50}.

e. Sinuosity (the ratio of thalweg length to valley length) is directly related to valley slope and inversely related to Q_s.

f. Qs is directly related to stream power* and concentration of fine material and inversely related to D_{50}.

13. The coefficients that govern these relations vary from stream to stream and generally cannot be used to produce quantitative predictions without considerable field data. Sometimes coefficients even vary from reach to reach on the same stream. Schumm (1977) reviews existing information regarding coefficients for these types of relations.

14. The above relations assume that other factors are held constant or are insignificant. Extreme or anomalous conditions can produce apparent contradictions. However, the relations are useful in a qualitative sense in that they explain streambank erosion which occurs in response to some major change in the channel or in the inputs of water and sediment. The fluvial system responds to changes as a system, so streambank protection at one site conceivably could prompt erosion at other sites. Nunnally and Shields (1984) presents a more detailed discussion of these and other similar relations.

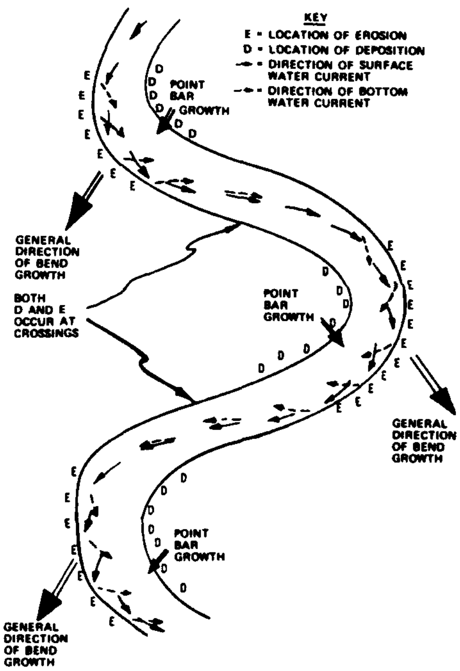

Figure 1. Migration of meander loop and cutoff development (adapted from Klingeman and Bradley 1976

15. River meanders gradually migrate downstream and grow outward (Figure 1). As the concave bank gradually erodes, the meander loop extends outward and draws closer at the neck or base. Chutes develop across low areas on the convex side during high flows. A natural cutoff may occur if one of these

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* Stream power = rate of energy loss per unit length of stream = (tractive force) x (velocity).

chutes enlarges enough to capture the flow and the river assumes a new, straighter alignment. A new meander loop will develop eventually, and the cycle will repeat itself.

16. The rate of meander loop migration (and associated streambank erosion) is governed by hydrology, upstream and downstream channel changes, the resistance of bank materials to erosion, and other factors. The planform (pattern) of meanders frequently is affected by the presence of "hard points" in the bank such as bedrock outcrops, cemented gravels, or clay deposits.

Local scale

17. Failure types or mechanisms. When the failure of a streambank at a specific site is considered, one or several of a number of mechanisms may be at work (Keown et al. 1977, American Society of Civil Engineers (ASCE) 1965). These mechanisms include:

- a. Erosive attack at the toe of the underwater slope, leading to failure of the overlying bank. Most of these failures occur during falling river stages, after water levels fall below midbank height.
- b. Erosion of the soil along the bank caused by currents.
- c. Sloughing of saturated cohesive banks incapable of free drainage, due to rapid drawdown.
- d. Flow slides (liquefaction) in saturated silty and sandy soil.
- e. Erosion of soil by groundwater seepage out of the bank.
- f. Erosion of the upper bank and/or the river bottom due to wave action caused by wind or by passing boats.

18. OCE (1981, Appendix C) identifies the above mechanisms and several others, and categorizes them as surficial bank deterioration mechanisms, bank failure mechanisms, or mechanisms that transport the eroded sediment away from the bank. Mechanisms additional to those listed above include freeze-thaw action, abrasion by ice and debris, and swelling and shrinking of clays. It is important to note that streams tend to exhibit the geomorphic relationships described above regardless of which erosion mechanisms are acting.

19. Bank soil characteristics. The characteristics of soils composing a given bank partially determine which erosion mechanisms act.

Surficial erosion is most likely to occur in deposits of granular material with minor amounts of clay-size particles. Section 32 Program research characterized erosion properties of different type banks (OCE 1981, Appendix C).

a. Rock banks. Rock banks normally are quite stable and subject only to quite gradual erosion and intermittent mass failure. Rock banks or beds on one side can prompt erosion of opposite banks (OCE 1981, Appendix C).

b. Cohesionless banks. Streambanks composed of cohesionless soils normally are highly stratified heterogeneous deposits (OCE 1981, Appendix C). Cohesionless soils consist of mixtures of silts, sands, and gravels. These soils have no electrical or chemical bonding between particles and are eroded grain by grain. Erosion of cohesionless soils is controlled by gravitational forces and particle characteristics such as size, grain shape, gradation, moisture content, and relative density (OCE 1981, Appendix C). Erosion of cohesionless soils is fairly well understood (Keown et al. 1977).

c. Cohesive banks. Erosion of cohesive streambanks is more complex to analyze than cohesionless banks due to the characteristics of soil particle bonding. Cohesive soils contain large quantities of fine clay particles composed of chemically active minerals which create strong chemical and electrochemical bonds between particles. Soil characteristics affecting cohesive soil erosion are the type and amount of cations in pore water, composition of the soil including the type and amount of clay minerals, and the type and amount of cations in the eroding fluid. Cohesive banks are more resistant to surface erosion but are more susceptible to failure during rapid lowering of water levels due to their low permeability (OCE 1981, Appendix C).

d. Stratified or interbedded banks. Stratfied banks are probably the most common bank type in natural fluvial systems (OCE 1981, Appendix C). The soils in stratified banks consist of layers of materials of various sizes, permeabilities, and cohesion. Where cohesionless layers are found interbedded with cohesive soils, erosion characteristics are determined by the erodibilities of the component layers and the thickness and position of the cohesionless strata. The layers of cohesionless soil are protected somewhat by adjacent layers of cohesive soils, though the cohesionless soils are still subject to surface erosion (Schnick et al. 1981).

Accelerated Erosion

20. The term "accelerated erosion" as used herein refers to erosion that is atypically high in magnitude and is different in nature than the erosion experienced at the site or reach in question in the recent past. Accelerated erosion may be due to factors acting at the site or elsewhere within the basin. Both natural events, e.g. high flows, and human activities such as land use changes can cause accelerated erosion. Three major causes of accelerated erosion are channel modification, reservoir construction, and land use changes. Navigation traffic and mining from the streambed are sometimes associated with accelerated erosion (OCE 1981, Appendix C).

Channel modification

21. Channel straightening and enlargement is sometimes accompanied by accelerated bed and bank erosion. Velocities and peak flows are often increased, and the channel may respond by enlarging, which results in bank oversteepening and failure. A wave of streambank erosion moves through the system (including tributaries) as the deepening or headcut moves upstream. The increased sediment yield may cause aggradation and/or widening downstream (OCE 1981, Appendix C).

Reservoir construction

22. Storage reservoirs tend to reduce sediment load and peak flows downstream. If the reduction in sediment load is significant, degradation tends to occur downstream. Sometimes this tendency is offset by the presence of a bedrock channel or other geologic control or by development of an armor layer. Aggradation may occur downstream of the reservoir if the reduced peak flows are incapable of transporting inputs of sediment from tributaries. Tributaries may experience severe erosion and headcutting if they are high during reduced stages on the impounded main stream (OCE 1981, Appendix C).

Land use changes

23. Human activities or natural events in the drainage basin may affect inflows of water and sediment, thus prompting bank erosion. Row crop cultivation, mining, timber harvesting, and overgrazing usually

result in increased runoff and sediment yield relative to a basin covered with natural vegetation. Urbanization normally increases frequency and magnitude of peak flows, with attendant channel erosion. Sediment yield is especially high during the construction phase, but longer term effects of urbanization on sediment yield depend on land use practices prior to and following development (OCE 1981, Appendix C).

PART III: STREAMBANK PROTECTION AND ENVIRONMENTAL EFFECTS

24. The purpose of this part is to describe streambank protection methods and construction and maintenance procedures. A review of environmental effects, both positive and adverse, is also given. This information is provided to enable the reader to understand and appreciate the environmental features of designs and practices presented in Parts IV and V.

25. Streambank protection is used to prevent loss of valuable land, failure or loss of structures built on or adjacent to eroding banks, and undesirable changes in channel alignment. Large-scale bank protection efforts are used on major waterways to train channels into alignments favorable to navigation and the passage of high flows. Channel widening and horizontal migration are also controlled.

Streambank Protection Methods

26. Streambank protection methods may be classified as direct or indirect. Direct methods involve placing materials such as stone, fabric, or vegetation in contact with the bank to shield it from erosive forces. Indirect methods involve use of structures to deflect erosive currents away from the bank and reduce velocities next to the bank. Jacks, fences, and jetties are methods of indirect protection.

Direct methods

27. Widely used direct bank protection methods include riprap revetment, concrete pavement, articulated mattresses made of concrete blocks and wire, asphalt, erosion-control fabrics and mats, and vegetation. Gabions (wire baskets filled with stone) and used auto tires may be used to construct either continuous revetments or structures for indirect protection. Longitudinal stone dikes, windrows of stone placed along and parallel to the bank toe, are another type of direct protection.

28. Construction of direct streambank protection is accomplished by removing trees and snags, grading the eroded bank to a more gradual

slope, and placing the bank protection material. Some underwater excavation may be necessary. A "filter" of gravel or fabric may be placed between the bank and the revetment material to reduce the leaching of soils out of the bank through interstitial openings in the revetment. Land- or water-based techniques can be used to prepare banks and place materials, depending on the size of the waterway, economics, and environmental considerations.

Indirect methods

29. Widely used indirect methods include dikes, jetties, or hard points made of stone or gabions that project into the channel at an angle to the bank; fences made of boards or wire; and jacks. Jacks, which are made by fastening the midpoints of three concrete or steel beams together at right angles to form a structure shaped similar to a toy jack, are placed in rows and strung together and anchored with cables.

30. Construction of indirect bank protection structures is quite similar to construction of direct methods. Normally, less bank grading and tree and snag removal are required for indirect methods, which reduces adverse environmental effects.

Environmental Effects

Classification of effects

31. Streambank protection works have both positive and negative effects on environmental quality. The effects of streambank protection are difficult to isolate, since bank protection is normally placed along streams with other types of major engineering works such as channel enlargement and straightening, impoundments, training structures, and levees. Activities in the drainage basin such as deforestation and natural events such as droughts and floods can overshadow influences of bank protection on aquatic biology and water quality. To properly assess the effects of bank protection, one must compare conditions with streambank protection to the eroding conditions that would

exist in the basin without the structure.

32. Environmental effects may be classified temporally and by type of impact. For example, increases in turbidity and suspended sediment caused by bank grading and other construction activities are generally minor and short-lived. Long-term impacts result from the physical stability imposed on the fluvial system. Rates of lateral migration are reduced, and new backwater habitats are not formed to replace those gradually lost to sediment deposition.

33. Over an intermediate time frame, the most significant effect of streambank protection may be to reduce erosion and sediment input to the channel. Structures made of rock or gravel may provide substrate for bottom-dwelling insects (fish food organisms) and increase overall aquatic habitat diversity. However, when viewed over an extremely long time frame, streambank protection works extensive enough to stabilize the channel and reduce or eliminate development of chutes, sloughs, and oxbows may result in a significant decrease in habitat diversity and quality. Consideration of effects is simplified if they are organized into four basic, interrelated categories: terrestrial effects, aquatic effects, aesthetic effects, and effects on recreational resources.

Terrestrial effects

34. Riparian zones and habitat diversity. Streambank protection measures are placed at the water-land interface, which is part of the transition region between upland and aquatic ecosystems known as the riparian zone. The riparian zone along a natural unaltered stream provides a diversity of habitat types that is ecologically desirable. The stream-riparian and riparian-upland interfaces provide habitat typically higher in wildlife use than equal areas of one type of habitat due to the so-called "edge effect." The elongate shape of riparian zones creates high edge-to-area ratios, provides migration corridors, and serves as a connecting link between isolated pockets of natural habitat (Henderson and Shields 1982). Frequently the riparian zone is the only natural wildlife habitat remaining in agricultural or urban areas.

35. Streambanks and riparian zones are quite important to the

aquatic ecosystem because they provide inputs of energy in the form of organic matter (twigs, leaves, and terrestrial insects), which falls into the channel from overhanging vegetation. Energy input from riparian vegetation is most important to small headwater streams that are normally covered with a canopy of vegetation. The organic input is processed by microbial action and shredded and fragmented by benthic macroinvertebrates. The processed organic material then is further processed into smaller particles by other macroinvertebrates. The fine particulate organic matter becomes a major energy input to downstream reaches (Vannote et al. 1980).

36. Riparian zones often contain all the necessary components for diverse and productive plant (nutrients and moisture) and animal (food, water, cover) communities. Physical and attendant biological diversity is created by small elevation differences that lead to different frequencies and durations of flooding, and by channel migration. Channel migration cuts into and destroys climax areas on the outside of bends and deposits point bars that are invaded by flood-tolerant species such as willow and cottonwood at low flows. As deposition and succession continue, new climax communities develop. Channel migration then causes the cycle to start over. Thus, at any given time the floodplain of an unaltered river contains several successional stages and exhibits a high level of habitat diversity (Henderson and Shields 1982).

37. The density and diversity of riparian vegetation are enhanced by relationships to groundwater and surface water supplies. The flooding regime and groundwater seepage patterns determine the available moisture and nutrient cycling within the riparian zone. The seepage patterns of groundwater to channel and from channel to floodplain are mediated by the riparian zone. Alterations such as reduction in flooding duration, land use changes, and bank preparation (sloping, shaping, or excavation) for placement of protection structures can result in decreased retention of moisture in the riparian zone. Dominance of plant species in this succession process is affected by plant tolerance of flooding and soil characteristics, e.g., moisture. The sere, that is, the vegetation successional stage, of a riparian zone affects habitat

suitability by determining the age, type, and density of vegetation (Brinson et al. 1981).

38. Wildlife effects. Effects of bank protection on wildlife are related to habitat changes caused by alteration to riparian vegetation. In some cases, bank protection can prevent loss of valuable individual trees and shrubs due to erosion and bank failure and thus preserve a narrow strip of natural vegetation that would have been lost due to erosion. Generally, however, large-scale bank stabilization degrades the quality of terrestrial habitats by disrupting the natural channel migration process responsible for vegetational diversity. Stabilization of streambanks can promote land use changes because of increased protection, and thus reduce the quantity of wildlife habitat (Henderson and Shields 1982).

39. Hehnke and Stone (1978) documented bird use of protected riprap and adjacent unprotected streambanks and nearby cultivated areas along the Sacramento River (Figure 2)*. Species diversity, the number of species per acre, was 71 percent lower on the riprapped banks than on the unaltered sites. The total number of birds per acre, avian density, was

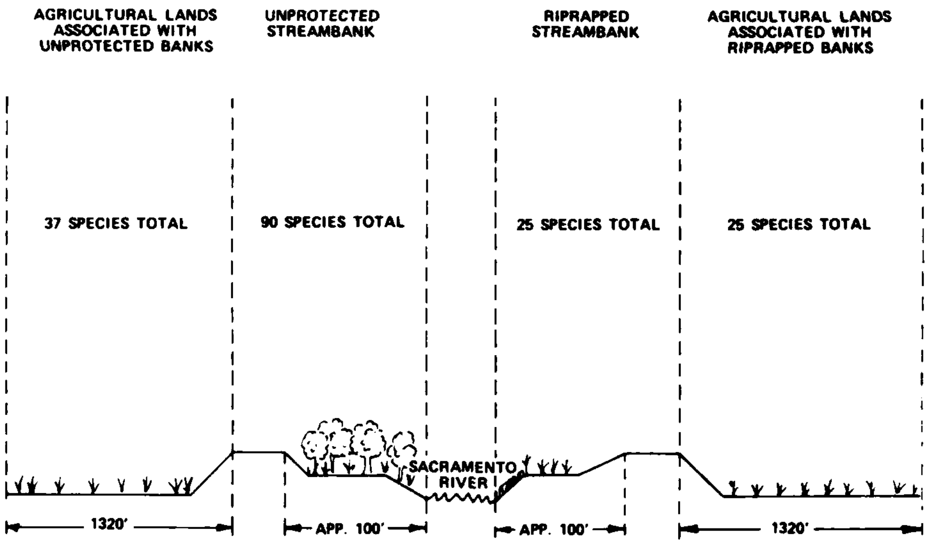


Figure 2. Bird use along natural and riprapped streambanks on the Sacramento River (adapted from Hehnke and Stone 1978)

* A table of factors for converting US customary units of measurement to metric (SI) units is presented on page 4.

93 percent lower on the riprapped banks. Avian use of associated agricultural lands showed similar differences. The lands adjacent to riprapped sites had 32 percent lower species diversity and 95 percent lower density than lands associated with unprotected banks. It was concluded that, at least for birds, streambank protection has a great impact on abundance and species diversity both on the riverbank and in adjacent parts of the basin.

40. The edge effect and linear distribution of riparian habitat are adversely impacted when extensive upper bank preparation and slope clearing are required. Such treatments are almost always detrimental to wildlife species such as muskrat, which live in dens or burrows in the streambank. Interruption of the riparian migration corridor by protection structures can adversely impact wildlife movement (Brinson et al. 1981). Streambank protection can improve or degrade access to the channel for wildlife.

Aquatic effects

41. Physical changes. Bank preparation and streambed changes required for streambank protection change the type and amount of habitat available for fish and bottom-dwelling organisms. Stabilization of the streambed and lower bank area usually requires the removal of riparian vegetation and fallen trees, stumps, and brush and the shaping of steep, curving, or undercut banks. The bank protection structure, usually made of some type of material not normally found in the stream, is inserted in place of the natural banks and snags. Bank protection can increase channel depth and current velocity and create more uniform hydraulic conditions (Henderson and Shields 1982). Stone placement results in creation of pools in low-flow areas between rock due to the riffles created at the surface (US Army Engineer District (USAED), Seattle 1982. The effect of these changes can be significant when enough of the bank line is stabilized to reduce the diversity of depths and velocities available in the stream (Henderson and Shields 1982).

42. Benthic effects. The benthic macroinvertebrate community, i.e., the bottom-dwelling organisms, includes those organisms that spend all or part of their life cycles on, in, or near the stream bottom

(substrate). The importance of the benthic macroinvertebrate community lies in its dual role in the aquatic ecosystem as part of the food web for fish and as a processor of organic material. This community includes insects, sponges, leeches, oligochaetes, crustaceans, mites, and molluscs. Habitat requirements of benthic organisms vary widely among species. The occurrence and abundance of species are determined by current speed, water temperature, substrate composition, and water quality (Hynes 1970).

43. Streambank protection structures impact substrate more than any other factor governing the benthic community. Most benthic organisms require a stable substrate--either gravel, cobble, or rock ledges--for attachment, or suitable firm, fine, cohesive sediment for burrowing. Noncohesive, shifting sediments are frequently devoid of macroinvertebrates. Placement of streambank protection structures requires an initial disturbance of benthic substrate (bank grading, etc.) but is followed by formation of substrate composed of structural material and the sediment stabilized by the adjacent structure. In many streams the placement of rock structures provides new habitat not available otherwise (Hynes 1970; Burress, Krieger, and Pennington 1982; USAED, Seattle 1982).

44. Several investigators have found macroinvertebrate populations on stone revetments and dikes with densities and diversities higher than nearby natural bank communities in both small streams (Winger et al. 1976, Witten and Bulkley 1975) and large rivers (Burress, Krieger, and Pennington 1982; Mathis et al. 1981; Beckett et al. 1983). Burrowing-type organisms benefit from stabilization of soft substrates and may populate stabilized natural banks underneath revetments (Mathis et al. 1981). Creation of moderate-flow habitat over riprap induces colonization by benthic species that prefer this habitat type (USAED, Seattle 1982). In streams with little or no stone substrate, as in most large river systems, riprap provides suitable macroinvertebrate substrate not previously available.

45. Witten and Bulkley (1975) compared the benthic productivity on stone riprap and on steel jacks, pilings, and fences used to protect

bridge crossings on Iowa streams. They found that steel structures were not colonized by invertebrates, but stone structures in the same streams were. Invertebrates that colonize structures become available for consumption by fish.

46. Fishery effects. Impacts on fish populations are harder to determine than for benthos, due to the mobility of fish. A fish captured adjacent to a revetment may utilize nearby natural bank habitat for much of its life cycle. Pennington, Baker, and Bond (1983) found similar fish populations adjacent to natural and revetted banks along the Lower Mississippi River. Revetted banks supported the highest percentage, by weight, of sport-commercial fish. Sport-commercial species are large, and thus may better withstand higher current velocities found next to revetted banks. Winger et al. (1976) found that riprap bank protection in a small warmwater stream provided cover for fish, particularly game fish. Fish fingerlings have been observed to utilize the protected habitat of riprap interstices (USAED, Seattle 1982). Elimination of snags, undercut banks, and other protective natural cover probably is unfavorable to many fish species.

47. Water quality. Effects of streambank protection on water quality normally are insignificant (Witten and Bulkley 1975). Little definitive information is available regarding the water quality effects of streambank protection. Project magnitude and site conditions probably are the controlling factors. Suspended solids and turbidity levels usually increase during construction of bank protection, but decrease after construction ceases and erosion is reduced. Removal of riparian vegetation tends to cause increases in water temperature and photosynthetic activity. The effect of removing riparian vegetation is insignificant in most of the waterways in which the CE works. In smaller streams, less than approximately 100 ft wide, the effects are more important (Stern and Stern 1980).

48. When chemically active materials are used in bank protection structures, adverse water quality effects can occur through leaching of toxic materials into the channel. During the Section 32 Program, steel furnace slag was used on the Ohio River because it is an economical

locally available material. Leaching of toxic materials occurred upstream of water intake structures (OCE 1981, Appendix D).

Aesthetic effects

49. The visual impact of streambank protection measures depends on the degree to which the measures contrast visually with their surroundings. The significance of aesthetic effects is a function of the number of viewers, their frequency of viewing, and the overall context. For example, the appearance of bank protection works in a heavily used urban park is more important than the aesthetic aspects of projects in industrial or extremely remote settings. Aesthetic effects can be positive or negative depending on preconstruction conditions and the perception of observers (Smardon 1979). Some individuals prefer the "artificial" appearance of a structure to caving banks and turbid water.

Recreation effects

50. Some types of bank protection improve access to the water's edge for sightseeing or recreation. Direct types with smooth surfaces, such as pavement or concrete mattress, offer easiest access. Some projects have incorporated recreation facilities such as access roads, parking lots, and boat ramps.

PART IV: STRUCTURAL DESIGNS

51. This part discusses designs and related environmental considerations for structural-type streambank protection. The designs selected for inclusion result in beneficial or desirable environmental effects, or at least minimize the adverse environmental consequences, even though they were not all originally formulated to meet environmental objectives. These direct and indirect methods include modifications to standard protection designs and recent innovative designs. Due to the relatively short time that some designs have been in place, definitive engineering and environmental performance data are unavailable.

Composite Revetment

Description

52. Concept. Streambanks may be divided into zones based on flow durations. The zonation scheme described below is developed more fully in the section Vegetation. Composite revetment utilizes different protection materials for each streambank zone (Figure 3). This streambank protection strategy is effective in a range of situations. It is particularly effective for deep channels where flows are concentrated along the bank line, but where depths or curvature preclude hard point systems and bank line or environmental conditions preclude windrow revetments. This composite revetment design was used extensively on Section 32 demonstration sites on the Missouri River.

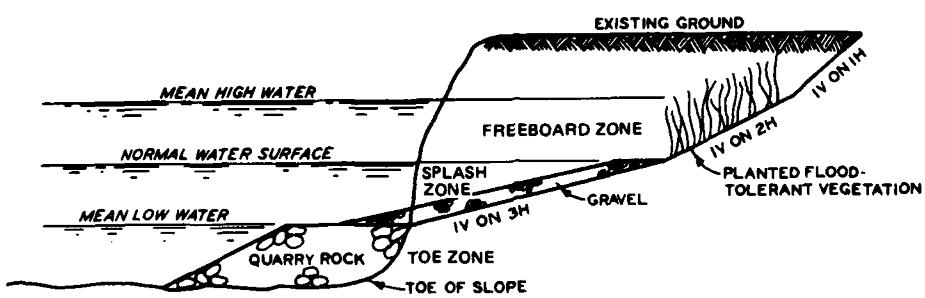


Figure 3. Typical composite revetment design (from Allen 1978)

53. Segments of composite revetments are interspersed with unprotected bank line segments. The lengths of the revetments and unprotected bank lines are determined by hydraulic conditions. On the Missouri, the revetments are a minimum of 400 ft long and unprotected bank line segments are a maximum of 300 ft long where the flow parallels the bank and a maximum of 200 ft long where the flow approaches at an angle of 45 deg or greater. A windrow refusal* 30-50 ft in length is placed upstream of the segmented structure to prevent flanking (OCE 1981, Appendix E).

54. Toe zone. The toe zone (Figure 4) is the portion of the bank below normal water elevation. This zone is subject only to river current erosion.

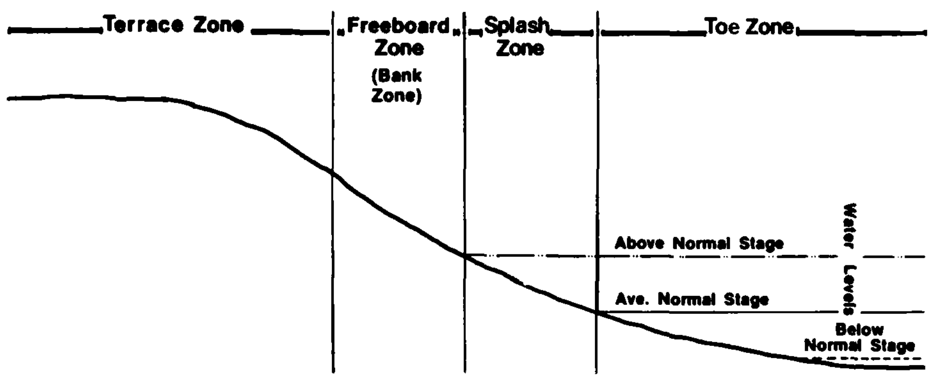


Figure 4. Streambank zones (from Logan et al. 1979)

Stone fill normally is used for toe protection. The most often used gradation for toe protection on the Missouri River is:

Weight or Size of Stone	Percent of Total Weight Lighter Than or Passing
500 lb	100
165 lb	35-60
3-in. screen	0-15

* A windrow refusal is a stone-filled trench buried perpendicular to the bank line. If erosion occurs upstream of the revetment segment, the refusal protects the revetment from flanking.

This gradation ensures that a reasonably dense blanket forms over the toe area.

55. Toe crown elevations normally are equal to the estimated mean low water elevations. Materials used for toe protection are placed on the natural riverbed, or minor excavation may be required to provide a stable toe structure. A layer of gravel is often placed over the toe crown to promote uniform sedimentation.

56. Low-grade materials may be used in the toe zone because it is normally under water and not exposed to wet-dry and freeze-thaw cycles. If stages lower than the toe zone elevation are likely, the low-grade material may be covered with a layer of stone. Chalk, limestone, soft sandstone, shale, and soil-cement mixtures have been used successfully in place of stone in the toe zone. Low-grade materials are used at sites where they are cost effective, most often where stone is not locally available (OCE 1981, Appendix E).

57. Splash zone. The splash zone is the zone of normal seasonal fluctuation, i.e., the portion of the bank between normal high water and normal low water. This zone experiences high erosive stress and is frequently exposed to wet-dry and freeze-thaw cycles, ice and debris movement, and wave wash. The upper bank (splash and freeboard zones) is sloped to increase hydraulic efficiency and give a suitable angle of repose for stone, gravel, or cobble protection. Stone gradation used most frequently for upper bank Missouri River composite revetments is as follows:

Weight or Size of Stone	Percent of Total Weight Lighter Than or Passing
200 lb	100
50 lb	35-60
2-in. screen	0-15

58. Freeboard zone. The freeboard zone, above the splash zone, is the portion of the bank above normal high-water elevation. This portion of the bank is exposed to weathering, high-stage erosion, wave wash, ice and debris flow, and traffic by animals and men. Bank protection for

this zone often incorporates vegetation with structures, or vegetation can be used alone depending on site-specific characteristics. Willow and cottonwood sprigs and a grass-legume mixture are planted, and natural invasion occurs (OCE 1981, Appendix E) Protection from overbank runoff may be provided by diverting runoff to natural drainageways or by using paved slope drains.

59. Upper bank experimental designs. Experimental designs utilizing a stone toe with various splash and freeboard zone treatments have been tested along the Missouri River. These upper bank treatments include: (a) a uniform blanket of gravel on a 1V:3H slope, (b) a blanket of stone, cobble, large gravel, or cellular concrete blocks on a 1V:2H slope; (c) filter cloth placed on a 1V:3H slope, anchored by a layer of gravel, cobble, or spalls at least 6 in. thick; (d) a layer of stone covering the bank from an elevation 3 ft below the construction reference plane to 3 ft above the construction reference plane on a 1V:3H slope; and (e) a layer of rolled clay placed on a graded upper bank covered by a thin layer of gravel (OCE 1981, Appendix E).

60. Environmental considerations. Composite revetments require less disturbance to the upper bank (splash and freeboard zones) than other revetment designs, i.e., reinforced, windrow, and riprap revetments. Construction by floating plant, which eliminates haul roads, further reduces terrestrial impacts. Wildlife habitat is enhanced by vegetation of the upper bank zones (Figure 5). Gravel placed over the toe protection material facilitates wildlife access to the channel. Rock and other materials used in toe treatments provide substrate for attachment forms of benthic macroinvertebrates. The visual impact of composite revetment is minimized because of the limited bank disturbance. Gravel promotes sedimentation and establishment of vegetation in the toe zone, and this, combined with vegetation in the freeboard zone, reduces the unnatural appearance of the structure.

Limitations

61. Composite revetment cannot be used where channel velocities and other conditions exceed the erosion resistance capabilities of the materials used in the splash and freeboard zones.

Figure 5. Composite revetment after establishment of vegetation

Performance

62. Composite revetments were effective in stopping erosion at the 23 Missouri River Section 32 demonstration sites at which they were used. Minor rehabilitation work was required due to upper bank scour and incorrectly constructed stone toes. All the experimental upper bank treatments were effective (stone, gravel, clay, installed vegetation, filter fabric, cellular concrete blocks); the cellular blocks were displaced at some sites by high bank runoff, but remained structurally sound. Placement of a stone toe and a thin layer of gravel above the toe was recommended because it is the simplest and least expensive and requires the least upper bank clearing (OCE 1981, Appendix E).

Costs

63. The cost of composite revetments for the Missouri River sites ranged from $46 to $170 (1984 dollars) per foot of protected bank line (protected bank line includes revetment lengths plus unprotected segments) (OCE 1981, Appendix E).

Reinforced Revetment

Description

64. Concept. Reinforced revetment consists of a stone toe placed parallel to the bank line. This protection strategy is most effective along bank lines with an underwater bench adjacent to a high bank. The stone toe protection may be placed along the toe or slightly riverward. At intervals along the stone toe, tiebacks are run landward into the bank (Figure 6). The bank area between the tiebacks is graded or backfilled. Section 32 Program demonstration sites on the Missouri River used segments of reinforced revetments with lengths of unprotected bank lines between the structures.

Figure 6. Reinforced revetment construction, showing tiebacks

65. Toe crowns were constructed to the normal water surface elevation, i.e., the elevation equaled or exceeded by the water surface 50 percent of the time. Tieback crowns were slightly lower than the toes at their point of intersection. The following stone gradation was used for the toe structures:

Weight or Size Stone	Percent of Total Weight Lighter Than or Passing
500 lb	100
165 lb	35-60
3-in. screen	0-15

66. The Section 32 Program evaluation recommended that future reinforced revetments be designed with the toe crown elevations equal to the tieback elevation. This would reduce stone requirements for the toe and make better use of the stabilizing ability of the tiebacks.

67. The tiebacks slope upward from the crown of the toe to several feet above the normal water surface elevation. Tieback stone gradation was as follows:

Weight or Size Stone	Percent of Total Weight Lighter Than or Passing
200 lb	100
50 lb	35-60
2-in. screen	0-15

Experimentation with different tieback spacings on the Missouri (75 ft to 160 ft center-to-center) revealed the optimum spacing to be 100 ft center-to-center along straight or concave banks where erosion is severe, and a minimum of 150 ft center-to-center along convex banks where flow streamlines are parallel to the bank line (OCE 1981, Appendix E).

68. The unprotected bank line areas between structures range from 40 to 400 ft on the Missouri River sites. It was determined that unprotected bank line areas should not exceed 300 ft where the flow is parallel to the bank or 200 ft where the streamlines approach the streambank at an angle of 45 deg or more. The minimum length of a single revetment segment should be 400 ft. On the Missouri River structures, a 50- to 75-ft windrow refusal is placed at the upstream end of the protected reach to prevent flanking.

69. Environmental considerations. Construction of reinforced revetment causes minor upper bank disturbances. The area disturbed by excavation for tiebacks gradually reverts to preconstruction conditions.

If the cells between the tiebacks are graded, backfilled, and seeded, terrestrial impacts are minimized (Figure 7). The segmented revetment design used on the Missouri resulted in virtually no adverse impact to the streambank and riparian habitat between revetment segments. Water-based construction, where possible, further reduces terrestrial impacts by eliminating the need for haul roads. The stone used for toe protection provides stable substrate for benthic macroinvertebrates. A gravel covering over the stone toe improves the visual appearance of the structure when the toe is above the water surface. When the revetment toe crown is submerged, the structure can present a hazard to small boats.

Figure 7. Vegetation established between tiebacks
(from OCE 1981, Appendix E)

Limitations

70. Reinforced revetment is effective in eliminating erosion, in both shallow and deep near-bank channel conditions, where extensive upper bank structural protection is not needed. Streambanks with erosion in the splash and freeboard zones require greater protection than provided by reinforced revetment.

Performance

71. Reinforced revetment was utilized at 23 of the Missouri River Section 32 Program demonstration sites. It proved effective in stopping erosion while minimizing the upper bank disturbance required for construction. Reinforced revetment proved very effective in eliminating future losses in severely eroding areas.

Costs

72. Costs for reinforced revetment on the Missouri River demonstration projects ranged from $63 to $202 (1984 dollars) per foot of bank line protected.

Windrow Revetment

Description

73. Concept. Windrow revetments consist of stone placed along the top of the bank. As the bank erodes, the stone is undercut and launches down the bank line. Windrow revetments are placed on streambanks that are actively eroding, but where some additional bank loss can be tolerated in order to construct a more desirable alignment. Because there is no construction on the eroding bank or toe, this revetment design is suitable for conditions where river flow is unusually deep and swift along the toe of the bank line. Windrow revetment can be used on long stretches of eroding, irregular bank lines (Figure 8). As the stone is "launched," a more uniform bank line is formed (OCE 1981, Appendix E; U. S. Fish and Wildlife Service 1981).

74. Construction may be either from land or water. Stone fill is placed in one of two ways, in an excavated notch at the top of the bank line (Figure 9) or in a trench excavated near the top of the bank, parallel to the bank line. Placement in a notch requires less bank clearing. The exposed surface of the stone is covered or backfilled with excavated material. Trench placement utilizes an excavation at least 2 ft deep. As further erosion takes place, the stone fill is "launched" down the bank and blankets the bank at a naturally established slope. Stone is then added on an as-needed basis until a stable equilibrium is

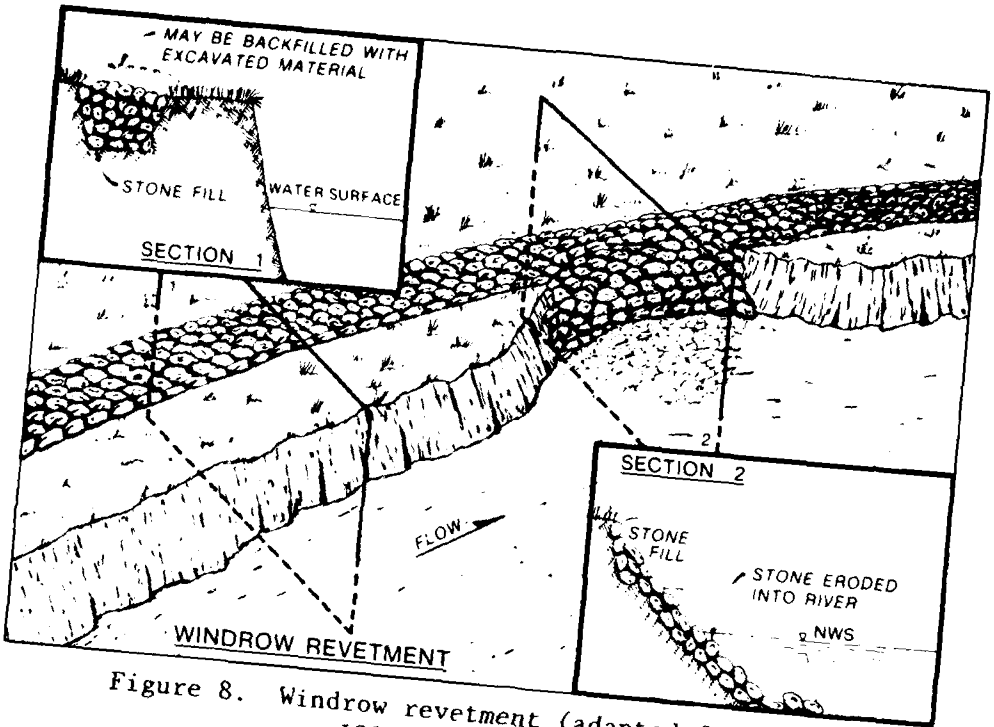


Figure 8. Windrow revetment (adapted from OCE 1981, Appendix E)

Figure 9. Notch placement of windrow revetment (from OCE 1981, Appendix E)

established, or unneeded stone may be removed and used elsewhere. After the structure reaches equilibrium, the bank slope revegetates quickly, often in less than a year. Site-specific conditions determine the amount of stone required to reach an equilibrium. Stone application rates on the Missouri River Section 32 demonstration sites range between 3.5 and 6.0 tons per linear foot. Normally, the stone gradation used for windrow revetment is smaller than for other revetment designs. On the Missouri, a 200-lb gradation was used:

Weight or Size Stone	Percent of Total Weight Lighter Than or Passing
200 lb	100
50 lb	35-60
2-in. screen	0-15

This gradation had a D_{50} of 7 to 8 in. This smaller gradation stone forms a more dense, closely chinked stone blanket. A denser protective blanket provides greater resistance to erosion of the underwater bank (OCE 1981, Appendix E). A similar gradation with a 400-lb top size has been used successfully on the Arkansas, Red, and Mississippi Rivers.

75. Environmental considerations. The habitat values of steep banks scoured by swift currents, where windrow revetments are normally used, are improved by the structures. Stabilization of a steep, eroding bank line by a less steep stone blanket improves access for wildlife. Naturally occurring vegetation on the structure and reversion of the excavated areas to preconstruction conditions improve the aesthetic value of the streambank. Aquatic habitat diversity is increased by the stony, stable substrate provided by the revetment.

Limitations

76. Windrow revetment requires some loss of additional land and cannot be used where further land loss is unacceptable. The eroding bank between the existing bank line and the stone windrow is "sacrificed." An additional swath several feet wide is required for construction of the windrow. This design usually is not used if the bank line is not already cleared; i.e., the presence of timber or structures may

preclude use of this design. Windrow revetment may be unsuitable for areas likely to receive heavy public use. The "launching" stones may be hazardous to recreationists.

Performance

77. The windrow revetments on the Missouri River performed well from an environmental standpoint because they replaced steep caving bank lines with a less steep streambank and stable substrate along the toe of the bank. In a number of cases, vegetation became established within a year after stone displacement. The revetments on the Missouri did require some repair efforts due to inadequate stone coverage or stone displacement along the toe. The erosion protection capabilities of these revetments in most cases has not been adequately tested (OCE 1981, Appendix E).

Costs

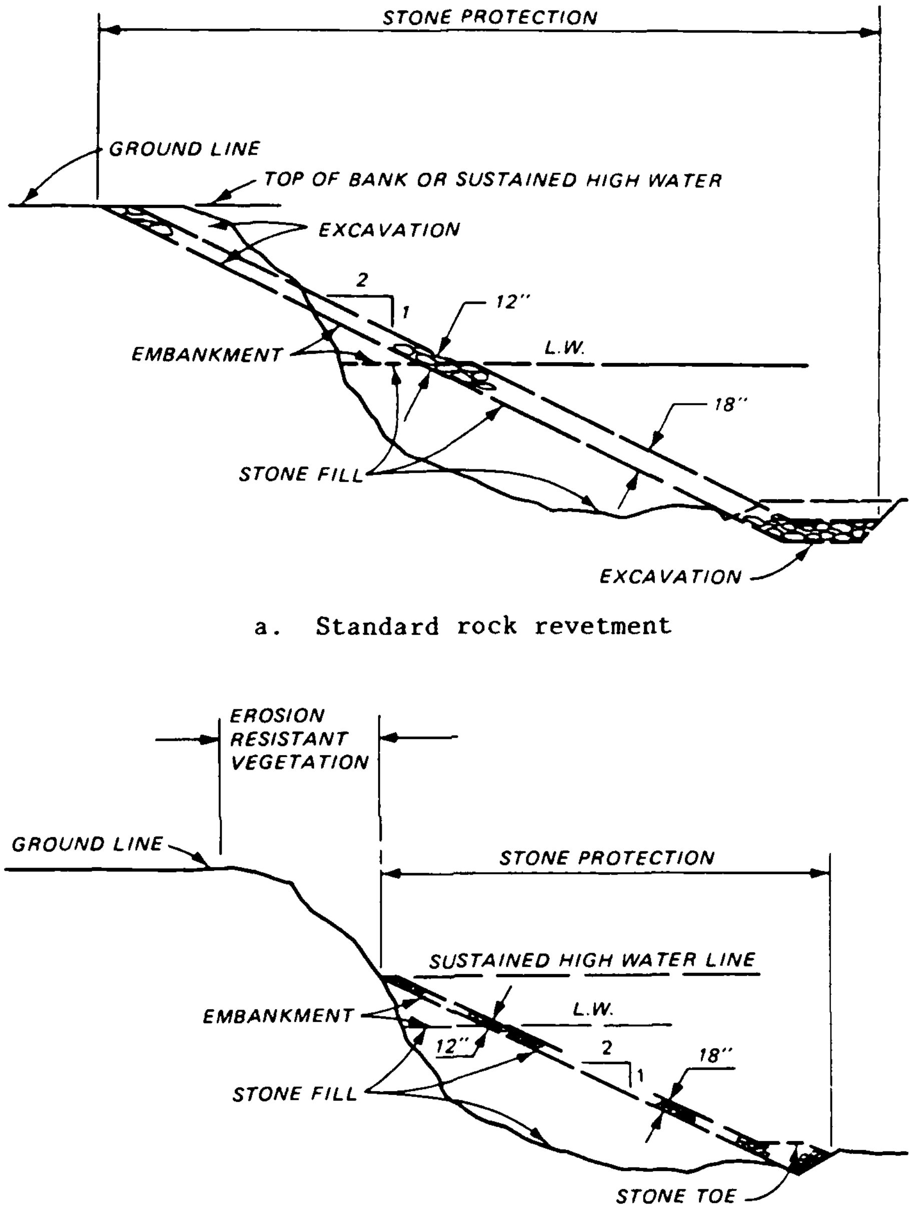
78. Costs for windrow revetment ranged from $58 to $180 per linear foot on the Missouri River demonstration projects (1984 dollars). The average cost of windrow revetment is cheaper than either reinforced or composite revetment (OCE 1981, Main Report and Appendix E).

Modified Revetment Design

Description

79. Concept. Revetment designs for basinwide application can be modified at some sites to achieve a more environmentally desirable design. The design flow may be reduced at sites where erosion conditions are such that protection to the original design flow elevation is not required. Along the upper Sacramento River, a modified revetment design was used, with a design flow lower than for other reaches of the Sacramento (Figure 10). The reduced flow was feasible because recreational boat wave wash is not as prevalent as in the lower reaches, channel velocities are lower (less than 10 ft/sec during flood flows), and the soils are cohesive (USAED, Sacramento 1975a).

80. The modified revetment design includes stone protection from the toe up to the sustained high-water elevation, i.e., the river stage elevation exceeded only 10 percent of the time. Above the high-water



a. Standard rock revetment

b. Modified design--top of revetment lowered to sustained high-water elevation

Figure 10. Rock revetment designs, Sacramento River (after USAED, Sacramento 1980)

elevation, the bank is planted with erosion-resistant vegetation and natural species are allowed to invade. A mixture of soft chess and ryegrass is seeded and fertilized (USAED, Sacramento 1975a).

81. Environmental considerations. Protection of upper bank vegetation and seeding of the disturbed portion of the upper bank preserves riparian habitat (USAED, Sacramento 1975b). No sloping or grading is done on the upper bank. Natural and planted vegetation on the upper bank creates a more natural appearance than standard revetment designs.

Limitations

82. Modifications to standard revetment designs are limited to situations in which the erosion protection properties of the design will be unaffected or improved by modification. Reduction of design flow elevation for upper Sacramento River revetments was possible because upper bank protection to the original design flow elevation was found unnecessary upon reevaluation. Incorporating vegetation in the design requires adjustments or additions to maintenance practices to include maintenance of the vegetation.

Performance

83. Use of the modified revetment design on the Sacramento River showed varying performance with the reduction in design flow. Some revetments had erosion above the design level, which undercut the bank protection from the landside. This occurred at sites that experienced the highest velocities.*

Costs

84. The modified revetment design was used in conjunction with the standard design, and costs are not separable. Reduced bank sloping and less stone tend to reduce costs, while seedbed preparation, planting, and maintenance requirements tend to increase costs.

Berm Preservation, Protection, and Restoration

Description

85. Concept. Where the riparian area is extremely restricted by

* Personal Communication, 1982, Mr. Fred Kindel, USAED, Sacramento, Calif.

levees, other structures, or cultivation, eroding banks may be prepared for revetment construction by filling instead of excavation. Along the Sacramento River, this technique has been utilized on the narrow strip between the riverside levee toe and the river, and the technique is referred to as berm restoration. When revetments are being constructed adjacent to badly eroding berms, an embankment is formed over the remaining portion of the berm (Figure 11). Natural or constructed berms may be seeded and planted after revetment construction. These berm areas enhance the stability and integrity of the levees and sometimes support the only remaining natural vegetation in an area due to intensive agriculture and urban encroachment.

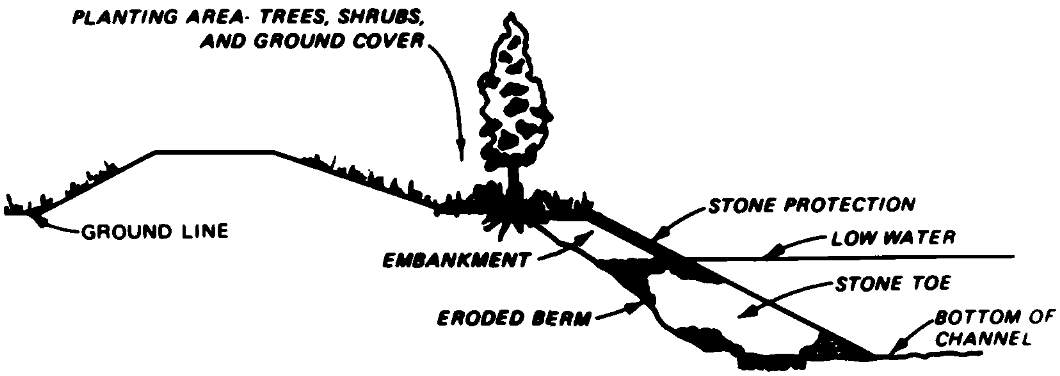


Figure 11. Berm restoration (from Mifkovic and Petersen 1975)

86. Maintenance of the levees, berms, and revetments along the Sacramento is normally accomplished by clearing all vegetation by disking, spraying, and burning. Although this clearing protects the levees and revetments from structural damage by root systems, increases visibility for inspection, and maintains the flood control capacity of the levee, natural regrowth of riparian vegetation is prevented.

87. Many of the early revetments on the Sacramento River were constructed using a 1V:3H slope. This practice results in substantial loss of berm width for slope preparation. A steeper slope of 1V:2H requires less berm width for slope preparation (Figure 12) (Mifkovic and Petersen 1975).

88. <u>Environmental considerations.</u> Berm preservation, protection, and restoration result in preservation of riparian habitat. Vegetation

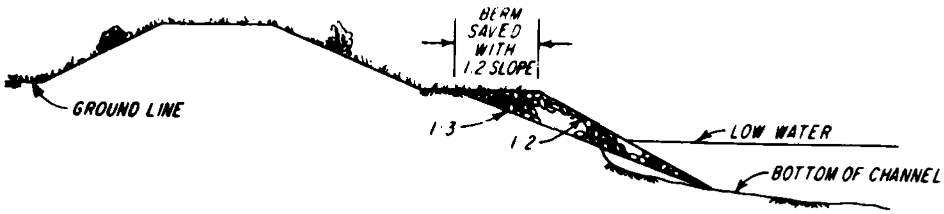


Figure 12. Berm preservation (from Mifkovic and Petersen 1975)

of the berm area enhances the edge effect and maintains a protective migration corridor along the channel. The appearance of the riparian zone is enhanced by natural vegetation along the berms. Although using steeper slopes preserves terrestrial riparian habitat, some investigators (Schaeffter, Jones, and Karlton 1982) have suggested using extremely flat slopes in order to provide shallow aquatic habitat. Natural cobbles and river gravel, which are sometimes used instead of riprap for aesthetic reasons, require 1V:3H or flatter slopes.

Limitations

89. Required maintenance of levees and revetments prohibits large vegetation from encroaching on levee embankments. Berm preservation and vegetation can complicate removal of vegetation from revetments and levee riverside slopes since the berm is between the two.

Performance

90. Efforts to maintain berm areas along the Sacramento River have restored their riparian nature without endangering the structural integrity of the levee system.

Costs

91. Preservation and restoration of riparian vegetation require modified maintenance practices that increase maintenance costs. Modifications to maintenance procedures include such things as pruning of shrubs and other actions to control the size, type, and density of vegetation.*

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* Personal Communication, 1983, Mr. Mel Schwartz, Levee and Stream Management Section, California Reclamation Board.

Toe Protection

Description

92. Concept. Stabilization of the toe area is critical for streams where bank erosion is caused primarily by toe erosion undermining the bank. In these cases, however, work on the middle and upper banks is often not needed. In such cases, environmental considerations are best served by preserving existing trees and shrubs above the toe (Figure 13). Revegetation of the bank above the toe protection depends on siltation and an adequate seed source, e.g., waterborne (Carlson 1982). Planting of woody species may be necessary to stabilize the banks until vegetation becomes established through natural invasion and sedimentation. Structural materials, e.g., stone riprap, fieldstone, or quarrystone, may be used to stabilize the toe area. The toe protection deflects flow from the bank and promotes sediment deposition behind the structure. Stone tiebacks running from the toe into the bank are often used at either or both ends to prevent flanking.

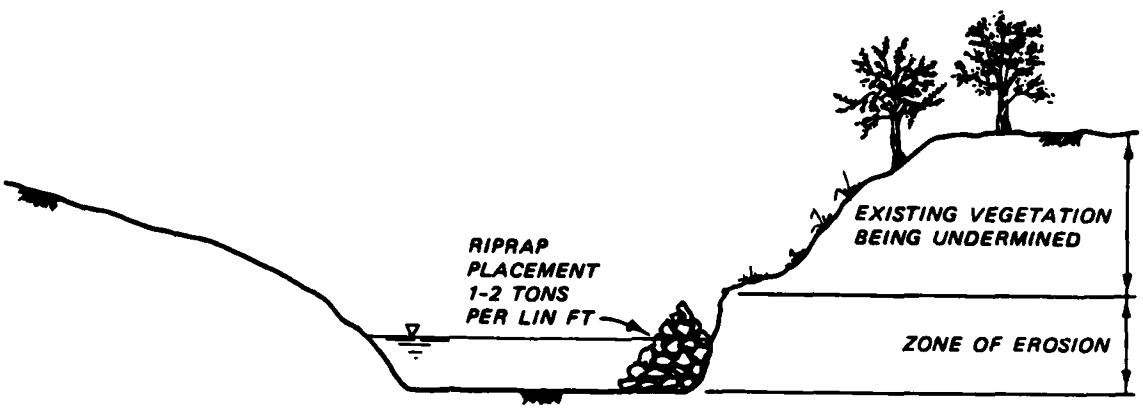

Figure 13. Toe protection design (after Personal Communication, 1981, Mr. Charles Elliott, US Army Engineer District, Vicksburg, Vicksburg, Miss.)

93. Environmental considerations. Toe protection is beneficial to terrestrial habitat because the riparian nature of the streambank is restored, either through vegetative treatment of the upper bank or invasion of native species to the stabilized bank (Figure 14). Clearing

Figure 14. Vegetation established on bank area of toe protection design

required for the placement of stone for toe protection along small channels may be reduced by using equipment within the channel or from only one side of the channel. The net effect of toe protection on riparian vegetation is far more positive than for complete revetment of the entire bank. The vegetation replaces an unstable bank with wildlife habitat and adequate access to the stream. Visual quality of the stream reach is improved by the riparian appearance of the stabilized bank. Access for recreation use is increased by stabilization; however, during high river stages the stone toe may be a boating hazard.

Limitations

94. The major limitation for toe protection is site characteristics. Erosion must be "correctable" using toe protection. When vegetation is used on the upper bank, monitoring and maintenance of vegetation is required during the establishment period. Such monitoring ensures that riparian habitat benefits are attained (OCE 1981, Appendix F).

Performance

95. Toe protection proved successful for streams in the Yazoo River basin, except in two cases:

a. Where channel instability was not arrested, i.e., bed degradation or headcuts continued, requiring rehabilitation of the structure.

b. Scour occurred above the toe protection, e.g., vegetation failed to establish or the bank was highly erodible.

Costs

96. Costs for toe protection in the Yazoo basin ranged from $41 to $113 per linear foot (1984 dollars). The number of tiebacks, amount of stone used (from 0.5 to 2 tons/ft), and upper bank treatment required contributed to the variation in costs (OCE 1981, Appendix F).

Excavated Bench Design

Description

97. Concept. The excavated bench method is used on straight reaches of small streams and employs vegetation and structural protection (Figure 15). The design is used where toe stability and lower bank scour are problems. The purpose of an excavated bench is to provide a suitable growing environment for woody vegetation. A bench area is excavated parallel to the channel, and a trench is excavated along the toe and filled with riprap. Topsoil is excavated from the upper bank and the trench to develop the proper slope for the upper bank (2V:5H), bench area (1V:5H), and the lower bank (1V:2H). The lower bank is protected

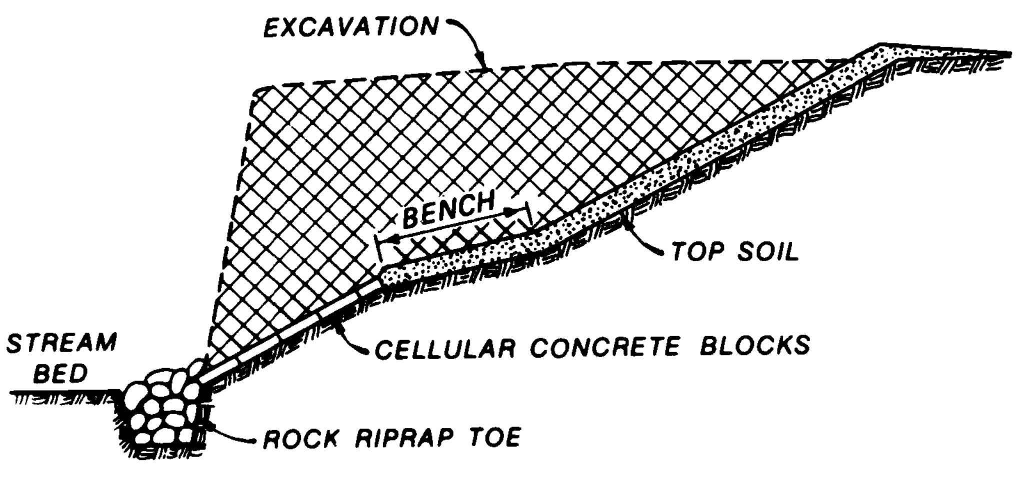

Figure 15. Excavated bench design (from Bowie 1981)

by stone riprap, cellular concrete blocks, or concrete cap blocks up to the approximate maximum water surface elevation for 90-95 percent of the annual storm events (Bowie 1981).

98. Environmental considerations. The vegetation included in the excavated bench design improves riparian wildlife habitat. Terrestrial habitat diversity is increased if a variety of woody and herbaceous species is established on the bench. The vegetated bench and slope areas result in a natural riparian appearance.

Limitations

99. The excavated bench design has been used only on straight reaches of small streams. The design may be ineffective on larger streams and would be unsuitable where upper bank scour is a problem. Until the vegetation becomes well established (first few growing seasons), maintenance is required to control or retard growth of unwanted plants. Where a good stand of vegetation is not achieved, replanting must be done.*

Performance

100. This design, as well as all of the other minimum protection designs used in the Yazoo basin, is effective in controlling erosion and establishing riparian vegetation. After two growing seasons, the herbaceous and woody vegetation showed good to excellent survival and groundcover rates. A number of storm events had inundated the bench area with considerable depths for varying periods of time, with no damage to the vegetation or streambank.*

Costs

101. The costs for installation of vegetation and structural components of excavated bench designs ranged from $32 to $62 per foot of bank line protected (1984 dollars). Other costs include channel excavation, seeding, disposal of excavated material, and soil preparation.*

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* Personal Communication, 1983, Mr. Andrew J. Bowie, US Department of Agriculture, Sedimentation Laboratory, Oxford, Miss.

Bank Sloping and Revegetation

Description

102. Concept. On a number of small, low-velocity streams in the Yazoo basin, bank erosion has been controlled along straight reaches by grading the eroding banks to a more gradual slope (2V:5H used in Yazoo basin) (Figure 16). The sloped bank is plated with topsoil, fertilized, and seeded (Bermuda grass or Alamo switchgrass was used in the Yazoo basin). No structural components are used. Herbaceous vegetation may also be planted, and native species are allowed to invade (Bowie 1981).

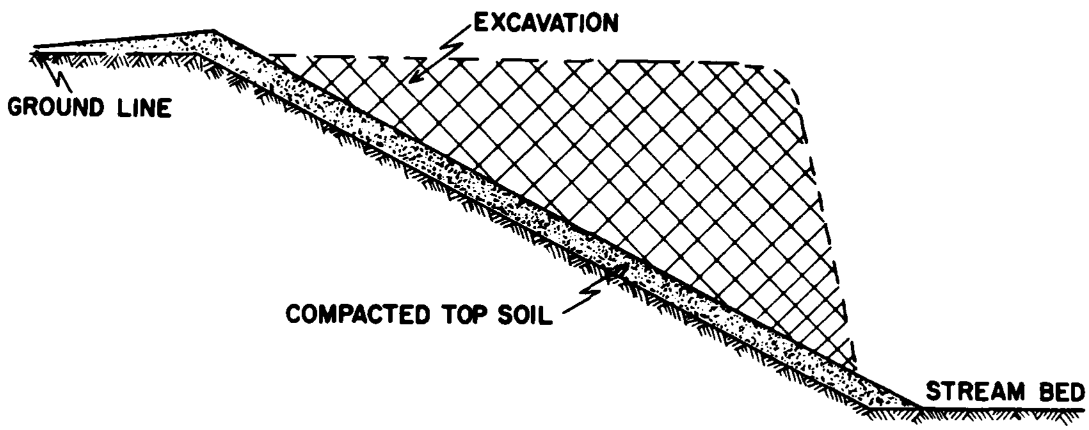

Figure 16. Bank sloping and revegetation (from Bowie 1981)

103. Environmental considerations. Wildlife species benefit greatly from the development of riparian habitat along the channel. The sloped banks provide access to the channel for wildlife and recreationists, and the absence of structure creates a natural appearance.

Limitations

104. The design requires greater excavation than structural protection because of the flatter slopes. This may require acquisition of more land and disposal of excavated material. Although the vegetation, both natural and planted, is desirable because of habitat and erosion properties, it must be maintained (Bowie 1981).

Performance

105. Bank sloping and revegetation have proven successful in

streambank stabilization and establishment of riparian vegetation on straight reaches of low-velocity streams. Bank sloping along the Yazoo River tributaries resulted in establishment of significant amounts of natural vegetation. Rapid and substantial natural invasion occurred after the banks stabilized, encouraged by favorable growing conditions (Bowie 1981).

Costs

106. Costs for the bank sloping design were not separable from costs for other designs tested on the Yazoo tributaries. Major cost elements include acquisition of rights-of-way for excavation and disposal, excavation, seedbed preparation, planting, and maintenance of vegetation.

Channel Relocation Design

Description

107. Concept. Channel relocation has been used to protect concave meander banks along some Yazoo River tributaries (Figure 17). Channel relocation reduces the sinuosity of the stream by smoothing the transition between bendway crossings by shifting the thread of maximum velocity to the center of the channel. Channel sinuosity is reduced, but the thalweg slope is changed very little. The design results in a flatter

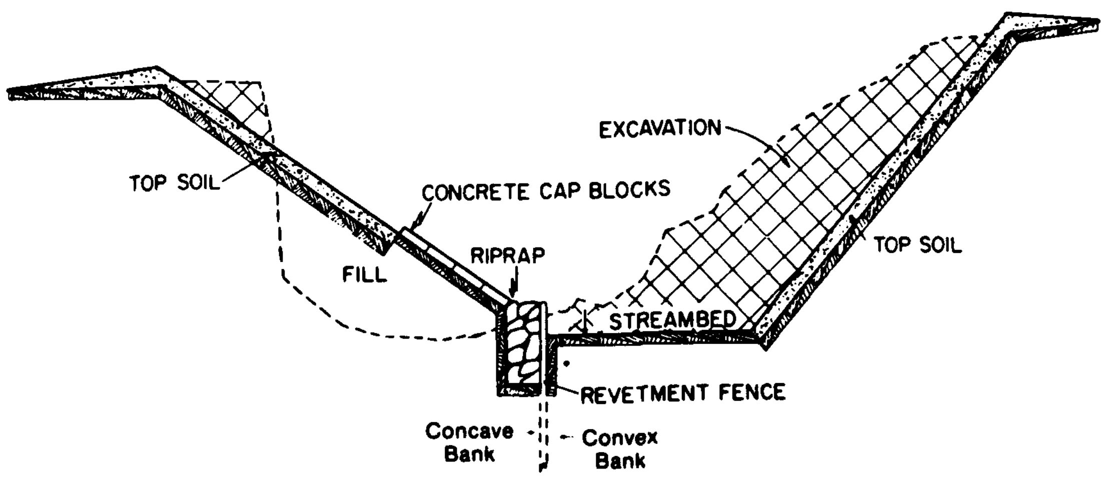

Figure 17. Channel relocation design (adapted from Bowie 1981)

concave bank slope without requiring additional land. By smoothing the transition between bendways, a more uniform bottom width is established (Bowie 1981).

108. On the concave bank, the toe is protected by placing a heavy-gage metal fabric (chain link) fence in the channel parallel to and some distance in front of the bank and excavating a trench behind the fence. The trench is then backfilled with stone riprap. The lower bank is protected to the water surface elevation for 90-95 percent of the annual storm events. Above the structural protection, the upper bank is sloped and planted with grass.

109. To accommodate relocation of the channel, the toe area of the convex bank is excavated. The upper bank area is also excavated and sloped. The toe area is planted in woody species, and the upper bank area is planted in grasses. The convex bank requires no structural protection except a hard point* placed at the upstream end of the bend (Bowie 1981).

110. Environmental considerations. Designs that include vegetation as a feature or that allow the establishment of vegetation provide greater potential for increased wildlife habitat diversity than do designs that include only structural components. The vegetation contributes a natural appearance to the middle and upper sections of the concave bank and to the grassed area of the convex bank. Aquatic habitat diversity will usually be reduced since an irregularly shaped channel with logs, holes, bars, and perhaps undercut banks is replaced with a trapezoidal section. However, stabilization of eroding banks and the addition of stable, stony substrate is probably beneficial to aquatic species.

Limitations

111. For this design to achieve the desired purpose, i.e.,

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* A hard point is a rock-filled structure placed at the upstream end of the bend, aligned perpendicular to the bank. If erosion occurs upstream of the protected bend, the hard point prevents flanking the structure. This hard point is similar to a windrow refusal and is not to be confused with the hard point bank protection structures.

relocation of the channel, the bendways must have acceptable geometry. The width of the low-water channel at each bendway must be fairly constant throughout the reach. A program of yearly or even seasonal maintenance is required to remove dead vegetation and control the density and types of vegetation on the slopes (Bowie 1981).

Performance

112. Channel relocation is effective in smoothing transitions between bendways and establishing riparian vegetation, i.e., grasses, woody, and herbaceous species along the banks (Bowie 1981). During the first 2 years after installation, this design experienced peak stage storm events without failure. Inspection after several years indicated no limitations in materials or design.*

Costs

113. Costs for the channel relocation design presented here are not separable from the other designs used at adjacent project sites in the Yazoo basin. Major cost elements include acquisition of rights-of-way; riprap and fencing; excavation; placement of riprap; fence construction; seedbed preparation; and maintenance.

Vegetation

Description

114. Concept. Vegetation often is a desirable component of streambank protection from environmental as well as economic and engineering standpoints. Vegetation normally is cheaper to install than structures. Riparian vegetation is capable of protecting the bank against erosive attack under certain erosive conditions (Seibert 1968). Appropriate species and planting methods vary so much from region to region that any CE design team considering use of vegetation in a bank protection scheme should utilize the expertise of local vegetation experts early in the design process.

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* Personal Communication, 1983, Mr. Andrew J. Bowie, US Department of Agriculture, Sedimentation Laboratory, Oxford, Miss.

115. Streambank stabilization by vegetation. Klingeman and Bradley (1976) point out four ways that vegetation protects streambanks. First, the root systems create a binding network that helps hold the soil together and increase the overall bank stability. Second, the exposed vegetation (stalks, stems, branches, and foliage) can increase the hydraulic resistance to flow and reduce the local velocities, causing energy to dissipate against the deforming plant mass and away from the soil--energy that otherwise might have exerted greater shear stress against the streambank soil. Figure 18 shows velocity profiles measured in a bare channel and a channel lined with Bermuda grass. Third, vegetation acts as a buffer against the abrasive effect of transported materials. Fourth, close-growing vegetation can induce sediment deposition by causing zones of lower velocity at the bank where shear stresses may become small enough to allow coarse sediment to settle out of the flow.

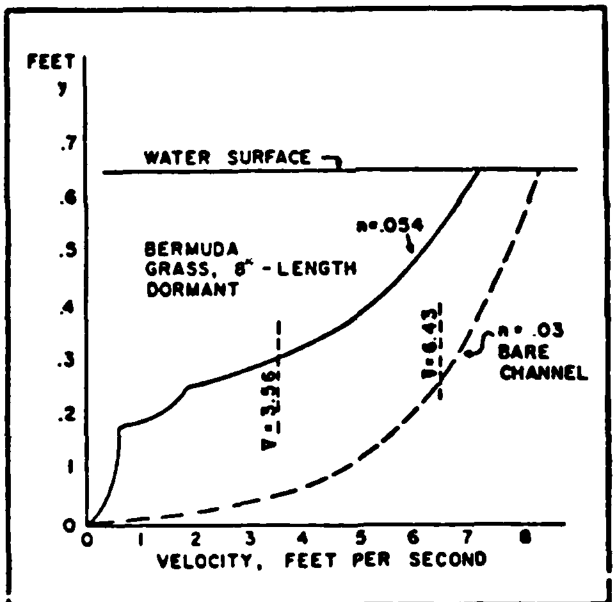

Figure 18. Influence of vegetation or variation of velocity with depth below water surface (after Parsons 1963)

116. Vegetation on unaltered streambanks. Streambank vegetation along an unaltered stream reach is dependent on hydraulic, soil, and hydrologic conditions. A natural alluvial river cuts into and destroys

climax areas on the outside of bends and deposits point bars that are invaded by flood-tolerant species at low flows. Distinct streambank plant communities develop in response to duration of inundation (Figure 19) (Seibert 1968). Most streambank protection designs replace the aquatic plant zone with structural protection and some combination of structural and vegetative treatment of the other zones.

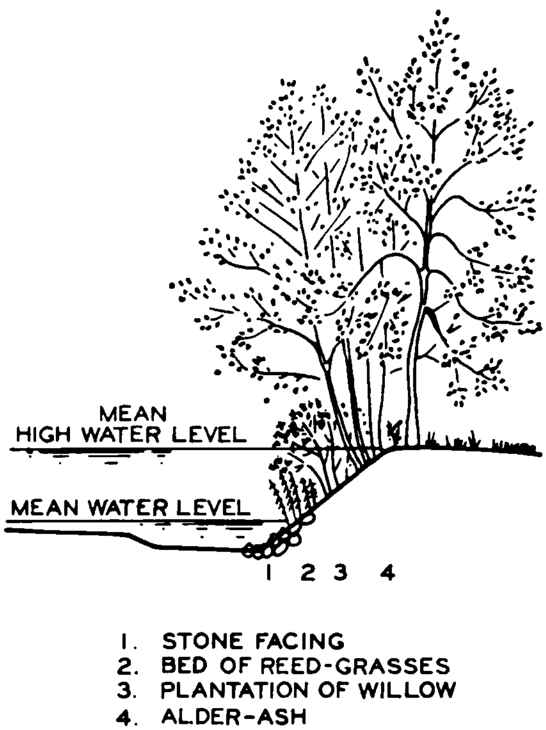

Figure 19. Vegetative community zones (after Siebert 1968)

117. <u>Environmental considerations.</u> Vegetation on the upper bank is desirable environmentally because it provides riparian habitat and is natural in appearance. Establishment of riparian vegetation is critical to preserving or restoring diverse wildlife populations which are characteristic of riparian zones (Seibert 1968). Structural protection measures tend to break the natural transition between water and the bank (Seibert 1968), whereas vegetative treatments provide a more natural visual transition.

Design considerations

118. Planning vegetation for streambank protection requires consideration of a number of factors to ensure that a design is successful. Site factors such as erosion rates or flow characteristics may preclude use of vegetation. Allen (1982a) sets out the following factors that must be considered in using vegetation.

a. Streamflow and flow characteristics. Determining the optimum vegetation types and planting times for a project is dependent on knowledge of the stream's hydrographic characteristics. Information regarding flood elevation and duration is required to select plant species and schedule planting (Allen 1982a). Plants are placed at different elevational zones on the bank based on their ability to withstand various durations of flooding and their attributes of dissipating wave and current energies. The USAED, Omaha, defined the zones presented in Figure 4 for use in preparing guidelines for the use of vegetation in streambank erosion control of the upper Missouri River (Logan et al. 1979).

(1) Splash zone. The splash zone is the portion of the bank between normal high-water and normal low-water flows. This section will be inundated throughout most of the year. The splash zone is exposed frequently to wave wash, erosive currents, ice and debris movement, wet-dry cycles, and freeze-thaw cycles. Thus, it is the zone of highest stress.

(2) Bank zone. The bank zone, sometimes called the freeboard zone, is that part usually above the normal high-water level. By definition, the bank zone is the portion of the bank inundated for at least 60 days once every 2 or 3 years. Stresses on the bank zone include periodic exposure to wave wash, erosive river currents, ice and debris movement, and traffic by animals or men.

(3) Terrace zone. The terrace zone is inland from the bank zone and is not usually subjected to erosive action of the river. Depending on the configuration of the bank, the terrace zone may include only the level area near the crest of the unaltered high bank or may include sharply sloping banks or high banks bordering the river. In many revetment designs, the terrace zone includes much of the cut (excavated) area of the constructed slope. Because of the infrequent inundation, the terrace zone is subjected to periodic dry periods with soil moisture dependent on rainfall.

b. Bank geometry. Eroding and undercut banks are often not suitable for establishment of vegetation. Banks too steep for planting require grading. Near-vertical slopes have proved impossible to vegetate.* Revegetation of slopes normally requires a slope of less than 1.5V:1H (Allen 1982a). The angle of repose suitable for vegetation varies with the soil type. On the Winooski River in Vermont, suitable slopes for the soils were (Edminster, Atkinson, and McIntyre 1949):

Soil Type	Slope
Heavy clay	1V:1H to 1V:4H
Medium texture	1V:3H to 1V:2H
Sandy or gravelly	1V:2H to 1V:4H

c. Site preparation. Plants require a growing medium that supports the plant and facilitates nutrient and water uptake. This may require covering slopes with a layer of topsoil high in organic matter (which may be stockpiled during grading operations) or adding soil conditioners such as lime, gypsum, or fertilizer (Allen 1982a).

d. Vegetation types. The vegetation used for streambank protection ranges from grassy species to large, woody species. All species should have some tolerance to flooding. Species suitable for various levels of inundation have been identified. For each CE Division, Whitlow and Harris (1979) identified flood-tolerant woody species and a few herbaceous species. Wentz, Smith, and Kadlec (1974) summarize this information for herbaceous plants.

Typical designs

119. Streambank zone vegetation. The streambank zones described above support different plant communities, primarily in response to daily and seasonal stream-level fluctuations.

a. Splash zone. Because it is often inundated, the splash zone cannot be successfully planted by direct seeding. During low water release periods, aquatic species may be transplanted. Shoots, slips, rhizomes, or clumps may be planted or reed rolls may be transplanted (Figure 20) (Logan et al. 1979). Reed rolls are especially effective in slow to moderately swift streams. Reed rolls are linear plantings that are placed in a trench. The rolls are developed by digging a trench 6 in. wide and deep. Wire

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* Personal Communication, 1983, Mr. Ivan Lines, Soil Conservation Service, Spokane, Wash.

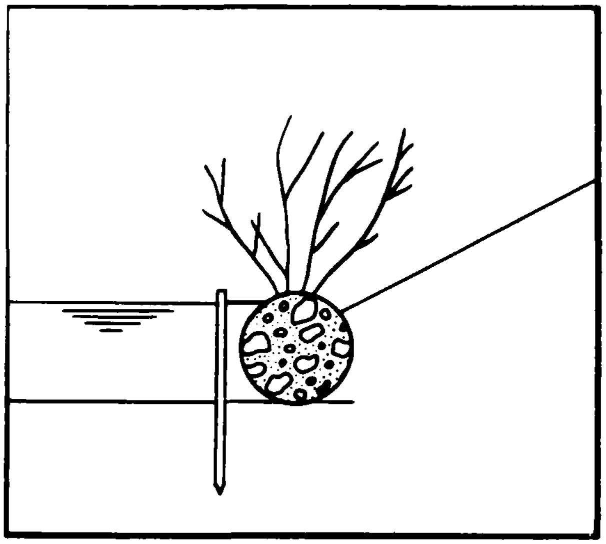

Figure 20. Reed roll (from Logan et al. 1979)

netting is then stretched from both sides between upright planks placed in the trench. Fill material such as coarse gravel or sod is placed on the netting. Reed clumps with roots are placed on the fill materials, covered, and then the sides of the netting are pulled together and fastened with wire. The upper edge of the roll should be approximately 2 in. above the water. The planks are removed and any gaps along the side are filled in with earth (Seibert 1968). The reed rolls and other transplants require mechanical or supportive structures, e.g., stakes, until the plants are well established (Logan et al. 1979).

b. Bank zone. Both herbaceous (e.g., grasses, clovers) and woody plants may be used in the bank zone. Sodding with flood-tolerant grass species in the bank zone is possible if only mild wave action is anticipated (Figure 21). The sod is held in place with small wooden pegs or wire netting until it roots adequately (usually 2-3 weeks) (Allen 1982a). Where more severe erosion conditions are anticipated, supportive structures composed of vegetative materials are used. Structures such as willow barriers and fascines have been used successfully in Europe (Allen 1982a, Seibert 1968).

(1) Willow barriers. Willow barriers (Figure 22) are interlaced willow switches 2 to 3 years old and 5 to 6 ft long that are placed on the bank perpendicular to the channel. The switches are interlaced so they are only 0.5 in. apart and are placed in a 6-in.-deep

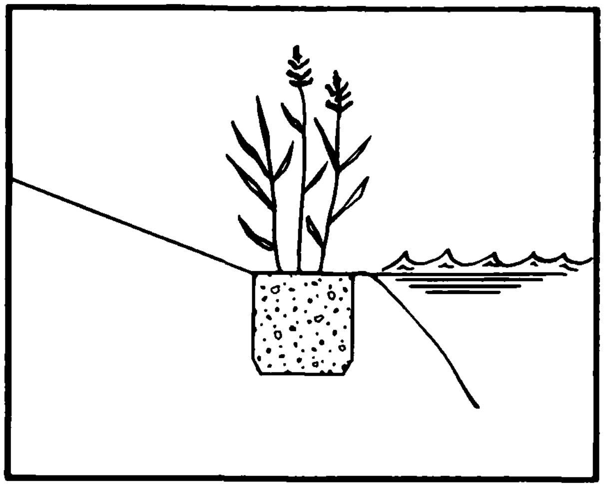

Figure 21. Sodding (from Logan et al. 1979)

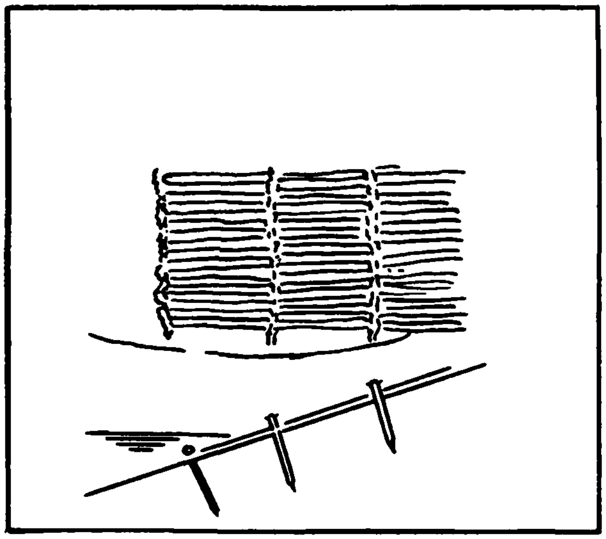

Figure 22. Willow barrier (from Logan et al. 1979)

excavation that is filled in later. Wire or willow hurdling (willow branches used as strapping) hold the willows together. The whole barrier is held in place by attaching wire or hurdling to stakes. The barrier is lightly covered with earth so that the branches are set in earth, but not completely covered. The willow switches sprout after planting (Allen 1982a, Logan et al. 1979).

(2) Willow fascines. Fascines are composed of switches of willow or other species packed together in a continuous roll 10 to 60 ft in length and 4 to 5 in. in diameter. The roll of willows is buried parallel or nearly parallel to the stream and is supported on the stream side by stakes (Figure 23). On streambanks subject to wave and current action, fascines may be planted diagonally to the wave action. Fascines are built from 2- to 3-year-old willow switches, 4 to 6 ft long, and are held in a tight roll by wire. The entire roll is attached to the stakes with wire. Rows of fascines are set at 3- to 4-ft intervals. The fascines are lightly covered with earth to encourage sprouting. The fascine structures themselves and the sprouting properties of the willows result in an integrated system of stems, roots, wire, and stakes to hold the bank in place (Allen 1982a). Fascines provide an effective deterrent to downhill surface movement of soil caused by downward water flow, wind action, trampling of wildlife and livestock and the forces of gravity (Logan et al. 1979).

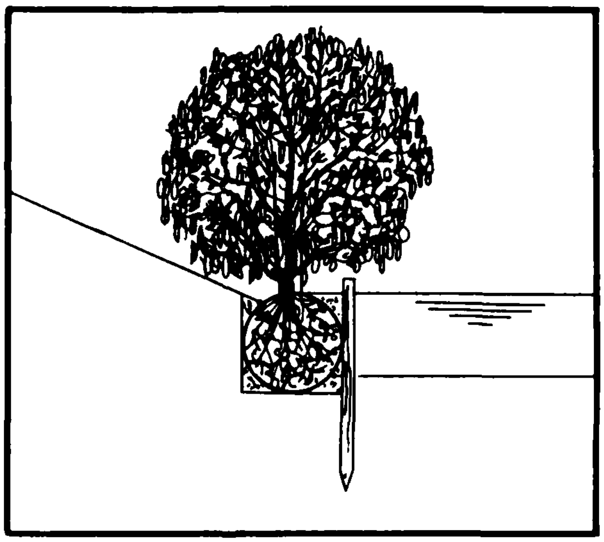

Figure 23. Cross section of fascine placement (from Logan et al. 1979)

(3) Root pads. Root pads may be used in addition to willow barriers and fascines on a supplementary basis. Root pads are composed of large clumps of shrubbery such as willow, dogwood, multiflora rose, or white mulberry (Logan et al. 1979). Sources for root pads include construction sites and private landowners.

c. <u>Terrace zone.</u> Although not usually subjected to erosive action, the terrace zone often requires revegetation after becoming denuded due to bank preparation activities or traffic by man, livestock, and wildlife. Revegetation schemes appropriate for the terrace zone include trees and shrubs. To stabilize the bank while the woody vegetation takes hold, grasses and legumes are seeded for a quick vegetative cover. Trees and shrubs are then transplanted into the grasses. Terrace zones with less than 1V:5H slopes can be planted with 1-year-old seedlings or container stock for woody species. Sites with slopes at least 1V:3H or steeper may require additional erosion control measures such as willow barriers or fascines. On these slopes, surface netting and mulching assist in seedling establishment. Larger size transplants are used on the steeper slopes. If surface drainage causes gully erosion on the slopes, a small furrow or ditch may be dug along the break of the terrace to divert or control the water. This drainageway can be sodded or planted with woody shrubs and trees to prevent erosion (Logan et al. 1979).

The US Army Engineer Division, South Atlantic (SAD), is undertaking a testing and evaluation effort of 17 different types of bioengineering methods, including those described above. These tests are being conducted at three test sites, encompassing 7000 ft of channel, along the Tennessee-Tombigbee Waterway. The detailed evaluation is due in late 1984.*

120. <u>Native and existing vegetation.</u> Designs should incorporate existing vegetation to the extent possible. Preservation of native species and natural invasion is often preferable because such vegetation normally has a higher survival rate. Establishment of native species should be through transplanting, rather than seeding, to overcome weed competition. On newly constructed slopes that have been planted or seeded, protective meshes or brush mats may be used to provide temporary slope and vegetative protection. These measures protect the bank from erosion, yet allow vegetation to grow through them. The mats can be constructed from species such as alder, dogwood, and willow, common along

* Personal Communication, 1984, Mr. John Lambert, Engineering Division, SAD, Atlanta, Ga.

many streams (Allen 1982b). Gray and Leiser (1982) provide guidance for selection and propagation of plants and for site preparation and maintenance.

Construction

121. Implementing a vegetative design requires adequate planning to ensure the vegetation is established before high or potentially erosive flows occur. Planting must often be coordinated with other construction activities, e.g., bank sloping or placement of stone for toe protection. Planting schedules should be based on the hydrograph. Normally, an optimum time to plant is immediately after seasonal high-water levels recede (Allen 1982b). The effectiveness of vegetative treatments generally depends on whether or not they have time to take hold prior to the high-water season (OCE 1981, Main Report). Contracting efforts for construction should take into account both the timeliness required for getting vegetation established in a growing season and the likely changes in construction specifications due to changes in site conditions caused by such things as high flows and erosion.*

122. The procurement of vegetation should commence as soon as the species are selected because of the lead time (often a year) required by nurseries. Vegetation may be procured by obtaining commercially available seeds and transplants from nurseries, growing transplants or seed plants or contracting nurseries to do it, and obtaining transplants from the wild. Site-specific native species are often not available commercially, but some nurseries may agree to collect native species and propagate them. A regional or local expert is the best source for guidance on selecting and locating plants. Lists of suitable nurseries are available from the Association of American Nurseries, 230 Southern Building, Washington, DC. Hunt et al. (1978) provide a list of nurseries and seed companies for numerous plants. The Soil Conservation Society of America publishes an annual guide, "Sources of Native Seeds and Plants," available from 7515 Northeast Ankeny Road, Ankeny, Iowa 50021.

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* Personal Communication, 1981, Mr. John Lambert, Engineering Division, SAD, Atlanta, Ga.

Maintenance and monitoring

123. An adequate regular maintenance program is required to ensure that a vegetative design attains its erosion protective capacity. Shrubs need 4-7 years to become effective, whereas grass and legumes produce cover in one growing season. Vegetation should be inspected at least monthly during the first growing season (Allen 1982b).

124. Newly planted vegetation must be protected from livestock and wildlife until it becomes established. This can be accomplished with three-strand barbed wire fences or by planting thorny vegetation such as multiflora rose at the top of the bank. The shrubs form a thorny thicket to deter animals from grazing on the bank. Replanting may be necessary if plants wash out (Allen 1982b).

125. After vegetation is established, the type, growth, and size of vegetation should be monitored. Trees planted in the terrace zone should be monitored to ensure they do not shade out planted grasses, herbs, and shrubs in the bank zone (Allen 1982b). This monitoring can be done aerially. Maintenance or replanting requirements depend on the amount of ground cover, stem densities, and plant survival rates (Logan et al. 1979).

Limitations

126. Vegetation must be suitable for the site and erosion conditions. Failure to withstand freeze-thaw and wet-dry periods can diminish effectiveness of a design (Allen 1982a). Soils present in a streambank may be unsuitable or not amenable to establishment of vegetation (Grissinger and Bowie 1982). Bank protection schemes composed entirely of vegetation were judged unsuitable for large rivers by the Section 32 Program (OCE 1981, Main Report). On the other hand, successful applications of vegetation along small channels can reduce the flow capacity by increasing hydraulic resistance.

127. Wilson (1973) noted increases in Manning's n from 0.022 to 0.045 after one growing season for a 50-ft-wide channel. After 6 years Manning's n was 0.070. Pickles (1931) reported Manning's n values of about 0.032 for 15- to 55-ft-wide clean drainage ditches and 0.050 for ditches with growths of weeds and bushy willows 3 to 40 ft high.

Obviously, only low, flexible vegetation species should be planted in or adjacent to a channel where flooding is a problem. Adequate protection is not provided until vegetation becomes well established, requiring a prolonged monitoring and maintenance program and possibly cooperative efforts (e.g., livestock control) by private interests (Edminster, Atkinson, and McIntyre 1949). Replanting is sometimes necessary.

Performance

128. Vegetation cannot be considered an economical cure-all for streambank erosion but should be considered in light of site-specific characteristics (Allen 1982a). Vegetation of the upper bank (the portion above mean normal flow) for revetment designs preserves or restores riparian habitat and improves the visual appearance of the streambank. To date, no evaluation of the habitat value of upper bank vegetation in streambank protection designs has been done. Conclusions drawn from the Section 32 Program demonstration sites indicate that much streambank erosion can be prevented by toe protection with vegetation on the upper slope, in lieu of construction to the top of the bank. This design approach proved successful on both large and small streams (OCE 1981, Main Report).

Costs

129. Costs for upper bank vegetation include those incurred in bank preparation, procurement of the plants, planting, and monitoring and maintenance. Table 1 shows the costs (1984 dollars) for a hypothetical hectare cut slope 3000 ft long with an average slope length of 30 ft located adjacent to a paved roadway. The cut had an assumed slope of 5V:4H (Gray and Leiser 1982). Price and wage inflation have made these published costs obsolete, but relative cost comparisons between methods should be valid (Allen 1982a).

130. Leiser (1983) documented the cost for preparing and planting 8000 willow cuttings at Lake Tahoe at $0.47 per cutting (cost converted to 1984 costs). This included labor, materials, and equipment. The willows were obtained at no cost from the US Forest Service (Leiser 1983).

131. Procurement costs vary with the source. Table 2 shows

Table 1

Comparative Equivalent Unit Costs for Selected Erosion Control Methods Used on Oversteepened Slopes

Revegetation	Unit Cost	% Labor	Cost per Hypothetical Acre
Unrooted willow cuttings*	$ 0.30/cutting	95**	$ 8,000†
Shrub transplants*	1.36/plant	60**	36,000
Bare-root seedlings*,**	0.63/plant	86**	17,300
Seed w/2800 kg/ha hydromulch	$0.15/yd^2$	30	1,200
Seed w/5600 kg/ha hydromulch	$0.23/yd^2$	30	1,900
Seed w/4500 kg/ha tacked straw	$0.18/yd^2$	30	1,100
Seed w/jute**	$1.47/yd^2$	70**	12,200
Seed w/paper fabric**	$1.61/yd^2$	68**	12,800
Seed w/excelsior**	$1.81/yd^2$	79**	14,200
Seed w/straw and plastic net**	$0.90/yd^2$	73**	7,050
Seed w/fiberglass roving	$0.67/yd^2$	N/A	5,250

* 16,200/ac, 0.5 yd on center.
** A large portion of these tasks may be performed by unskilled Conservation Corps laborers.
† When more than one type of planting is used, costs should be averaged.

Table 2

Costs of Plant Materials from Different Sources (from Logan et al. 1979)

Type of Plant Material	Sources: Government	Private	Native Stock	Contract
	Cost Per Plant			
Bare-root 15-24 in. minimum size	$0.11-$0.25	$0.14-$0.49	$1.37-$2.06	$0.11-$2.06
Container-grown 2 × 2 × 8 in.	$0.55-$0.69	$0.69-$2.06	N/A	$0.69-$2.06
Larger container	N/A	$2.06-$10.28	N/A	$2.06-$10.28

Note: Transportation costs are normally calculated at 20 percent of cost of plant material.

average costs for woody species from different sources (1984 dollars) (Logan et al. 1979).

Tree Retards, Pendants, and Revetments

Description

132. Concept. Methods for streambank protection utilizing trees and brush have been used as a single protection treatment and as a component of protection schemes. Mats and piles of brush or small trees may be placed on eroding banks, and whole trees may be anchored to the bank to deflect erosive flows (OCE 1981, Main Report and Appendixes E, G, H; Illinois Department of Conservation 1983). Local flow velocities are decreased by the partial screening of the banks, resulting in sediment deposition and formation of sandbars. Vegetation such as willows and cottonwoods may become established on these sandbars (Lines, Carlson, and Corthell 1979). Mats and deflectors made of natural vegetation are subject to damage and destruction by ice, wildlife, and high flows (OCE 1981, Appendix E).

133. Environmental considerations. Submerged trees and brush placed in streams provide protective cover beneficial to fish by replacing habitat lost through removal of snags, log jams, and organic debris (Hynes 1970). The vegetative structures reduce stream velocities near the bank, providing resting and maintenance habitat for fish. The structures themselves provide hiding cover and can serve as spawning areas (Gore and Johnson 1980). Structures made of vegetative materials have a natural appearance.

Designs

134. Tree retards. Experimental tree retards generally proved ineffective on the Missouri River due to damage to the structures. The tree retards were made of locally available trees placed perpendicular to the bank (Figure 24). Tree retard units of two trees, 30 to 40 ft in length, were placed 100 ft apart. The trees were anchored below normal water level by cables and a 55-gal concrete-filled drum. The butts of the trees were placed in a trench excavated from the channel to a

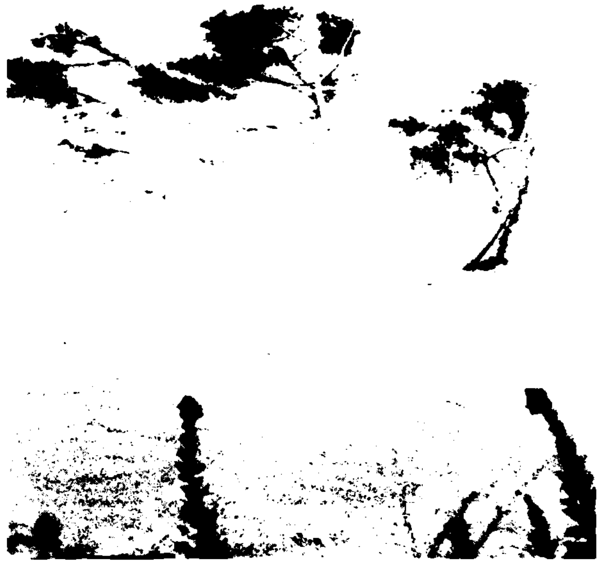


Figure 24. Tree retards (from OCE 1981, Appendix E)

point about 5 ft i.to the bank and backfilled with stone. The trench provided a stone root to anchor and protect the landward end of the retard. The branched portion of properly designed tree retards catches debris and sediment, causing small bars to form in the gaps between the tree retard units (OCE 1981, Appendix E).

135. Tree retards have been used on small streams to effectively eliminate local erosion problems. Herbkersman (1982) presents an approach to streambank protection involving several components developed by George Palmiter for use on small midwestern streams. These techniques require minimal clearing and no bank excavation or sloping. Manual labor is used to remove log jams, fallen trees, and other debris that force flows against the streambank. Protection of eroded or eroding banks is accomplished by building retard-like structures with large, brushy tree tops or piles of logs and branches (Figure 25). The vegetative material is secured upstream from where erosion is occurring with the butt end of the trees facing upstream. The brush piles deflect the flow away from the eroding bank. Series of several brush piles are necessary to protect long reaches of eroding bank line. Properly

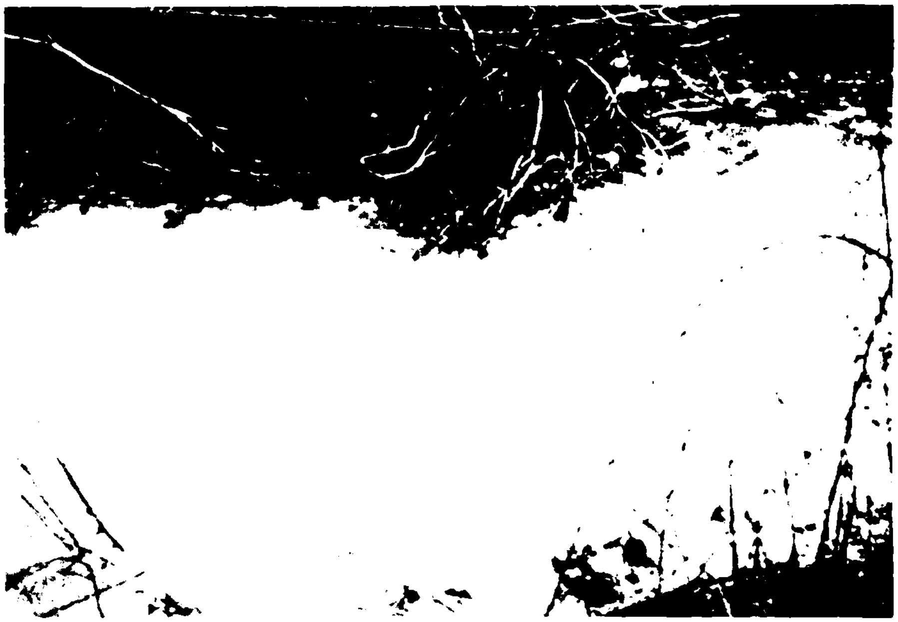


Figure 25. Tree tops placed against bank
(from Herbkersman 1982)

constructed brush piles will induce sediment deposition within the pile, anchoring it in place. Flood-tolerant species such as willows may then be planted on the sediment deposits. Edminster, Atkinson, and McIntyre (1949) describe a tree retard design, similar to the Missouri River design described above, which was tested along the Winooski River in Vermont. Trees used were 2-3 ft in diameter at the butt.

136. Tree pendants. A series of trees placed parallel to the streambank was used successfully on the Van Duzen River in California, on the Lower Chippewa River, Wisconsin, and on small streams in Oregon by the Soil Conservation Service (OCE 1981, Appendix G; Lines, Carlson, and Corthell 1979). On the Van Duzen River, a third of one 900-ft reach was protected by tree pendants. The rest of the reach was protected by pile fences. Along the face of the eroding bank line, whole trees, 40-50 ft long, were placed in a pattern overlapping the next upstream tree by one-third. Locally available redwoods were used (Figure 26). During cutting and transportation of the trees, portions of the root system broke off. The branches of the redwoods were brittle and many were lost, so that only the trunk and a few limbs survived placement.

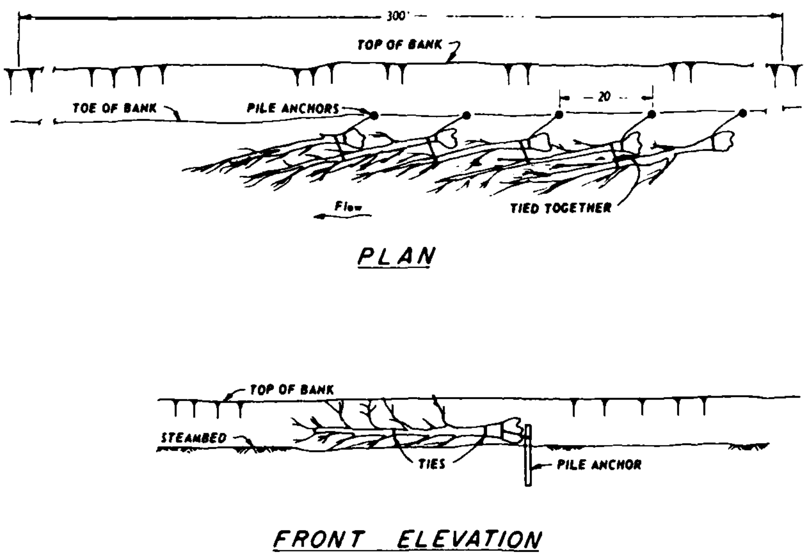
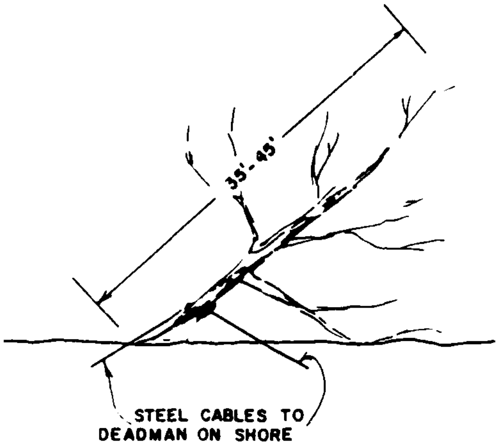


Figure 26. Tree pendant design (from OCE 1981, Appendix G)

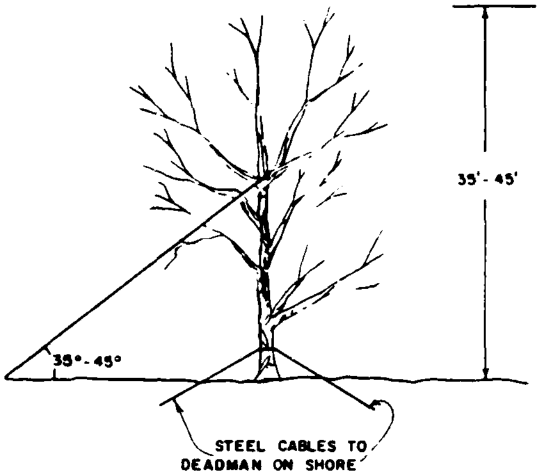
Each tree was anchored to a deadman on the bank and tied to adjacent pendants with wire rope. The pendants were designed to withstand current velocities of 8 ft/sec against the bank and 5 ft/sec along the length of the pendants (OCE 1981, Appendix G).

137. A similar design was used on the Lower Chippewa River near Eau Claire, Wisconsin. Along a straight reach of the river, the trunks of large trees (35-45 ft) were cabled to deadmen on the bank. On one section, the trees were angled downstream from the bank, spaced 30 ft apart (Figure 27a). Immediately downstream, trees were placed perpendicular to the bank, at various spacings (Figure 27b).

138. <u>Tree revetments.</u> In Wyoming, conifers were used on the Salt River to form revetments along concave bends (Figure 28). The revetments provided more permanent protection (estimated life is 10 years) than temporary emergency measures (Wyoming Game and Fish Department 1980; Line, Carlson, and Corthell 1979). The trees are protected at the upstream end by a rock deflector and are anchored by trees and deadmen on the bank (Figure 29). The trunks and branches of the trees in the river provide extensive trout habitat (Wyoming Game and Fish Department 1980).



a. Trees angled downstream



b. Trees placed perpendicular to bank

Figure 27. Tree placement on Lower Chippewa River (from OCE 1981, Appendix G)

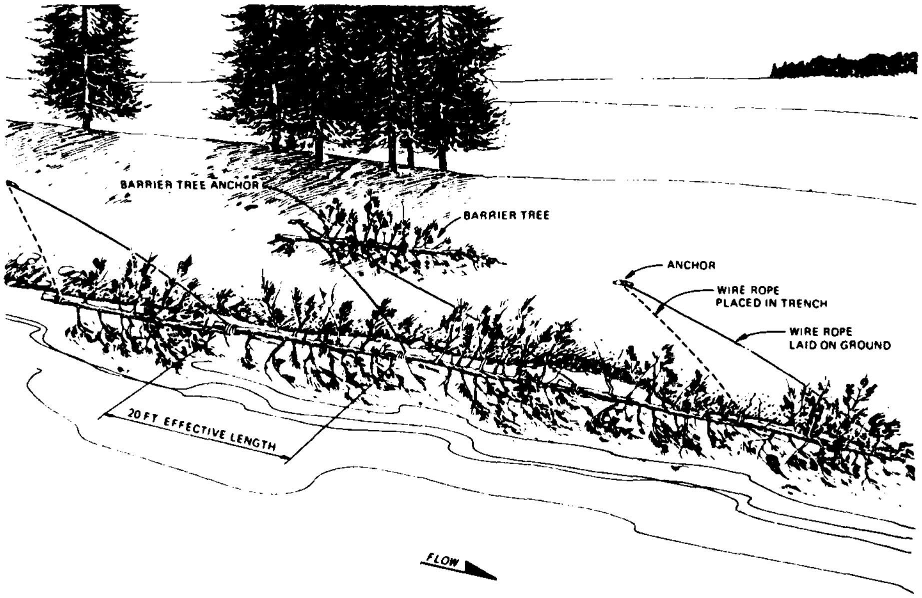


Figure 28. Conifer revetment design used on Salt River, Wyo. (adapted from Wyoming Game and Fish Dept. 1980)

139. A tree revetment scheme was used on a 680-ft reach of the Tanana River, Alaska. The revetment consisted of trees, mainly spruce, with and without root clumps. The trees were placed perpendicular to

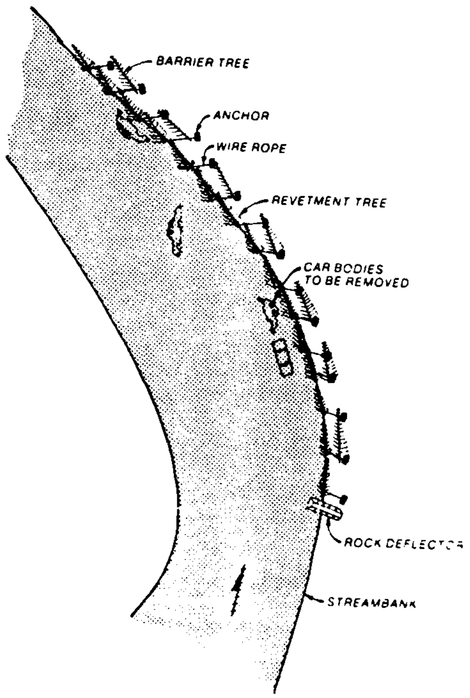


Figure 29. Alignment of trees, deadmen, and anchors on Salt River revetment (adapted from Wyoming Game and Fish Dept. 1980)

the bank with only the end of each tree (butt end of sawed trees and root clump of whole trees) remaining on the bank (Figure 30). The revetment was composed of 51 groups of single and multiple trees. The single trees or tree clumps were anchored to deadmen buried on the bank. The revetment was placed by pushing the trees into the channel after assembling them on the streambank. The current carried each tree downstream to swing it into the river bank. The anchor cables were then tightened to stabilize the revetment. The trees or tree clumps overlapped each other, but not to the extent of the redwoods used on the tree pendants.

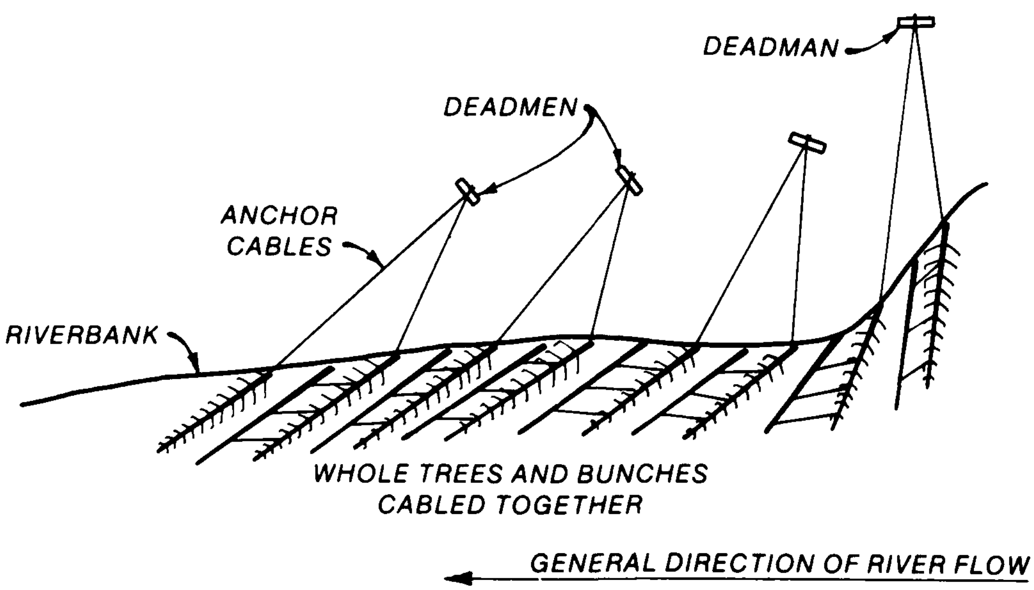


Figure 30. Tree revetment design (from OCE 1981, Appendix H)

140. The trees with root clumps were more effective as a revetment because the trees with roots stayed in the original position to a greater extent. The trees without root clumps were ineffective because they tended to float at the water's edge. Some of these trees were deposited on the riverbank during high flows. Clumps of less than three trees were less effective than clumps with three or more trees.

Limitations

141. Tree retards, pendants, and revetments are susceptible to damage or failure due to ice, high-flow conditions, beavers, and vandalism (used for firewood). Wood not continuously submerged decays within 5 to 10 years. Trees or brush must be available close to the erosion site.

Performance

142. Of the designs examined, those using trees in conjunction with other protection methods such as tree pendants proved more effective than single treatment designs, i.e., tree retards. The erosion protection capabilities of the designs presented above are varied.

143. Tree retards. On the Missouri River, most tree retard systems proved ineffective because of damage by high flows, ice, and beavers within 1 year after construction. It was noted that tree retards are not effective if sandbars do not develop along the bank line (OCE 1981, Appendix E). Tree retards installed along the Winooski River provided adequate protection for 4 to 5 years, but rotted and lost their effectiveness within 9 years.

144. Tree pendants. The tree pendants on the Van Duzen River were effective in controlling bank erosion (OCE 1981, Appendix G). It was observed that part of the success of this treatment was due to movement of the thalweg away from the bank.*

145. Tree revetments. The tree revetment installed on the Tanana River was a partial failure due to the inability of the rootless trees to resist flotation or displacement by flows (OCE 1981, Appendix H).

Costs

146. Available costs for these designs are as follows:

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* Personal Communication, 1983, Mr. Ted Albrect, US Army Engineer Division, South Pacific.

Design	Location	Cost
Tree Retards	Missouri River	$52/ft of retard $27/ft of bank protected
Tree Pendants	Van Duzen River, Calif.	$109/ft of bank protected
	Lower Chippewa River, Wis.	
	Trees anchored at angle to bankline	$10.80/tree
	Cables anchored trees parallel to bankline	$6.60/tree
Tree Revetment	Tanana River, Alaska	Costs inseparable from total project cost

Gabions

Description

147. Concept. Gabions are rock-filled wire baskets that are used for bank protection. The baskets are wired together to form continuous structures (Burroughs 1979) (Figure 31). The wire mesh is galvanized or coated with polyvinyl chloride (PVC) to deter corrosion. The wire baskets are assembled at the project site, wired together, and filled with rock. A gabion structure usually is constructed by laying a support apron of gabions and then stacking gabions in a stairstep fashion on top of the apron (Figure 32) (Keown et al. 1977). Gabion structures are flexible so some shifting of the underlying banks is not detrimental. Less site preparation and less skilled labor are required for construction of gabion works than for rigid linings (Shields and Palermo 1982). The rock is loaded by mechanical means, e.g., dragline, but unskilled labor is required for arranging the baskets in the structure (Burroughs 1979). Sedimentation often occurs between the rocks inside the baskets, and vegetation becomes established.

148. Gabion works are used in place of bank linings such as riprap or concrete. These structures provide permeable protection, important where hydrostatic pressure or bank seepage is a problem. Gabions are used on slopes that are too steep for riprap (greater than 1V:2H).

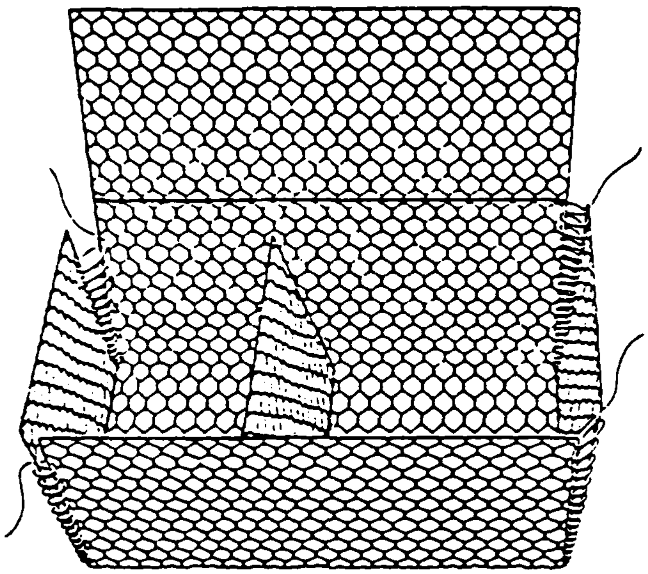

Figure 31. Typical gabion cage used for revetment (from OCE 1981, Appendix H)

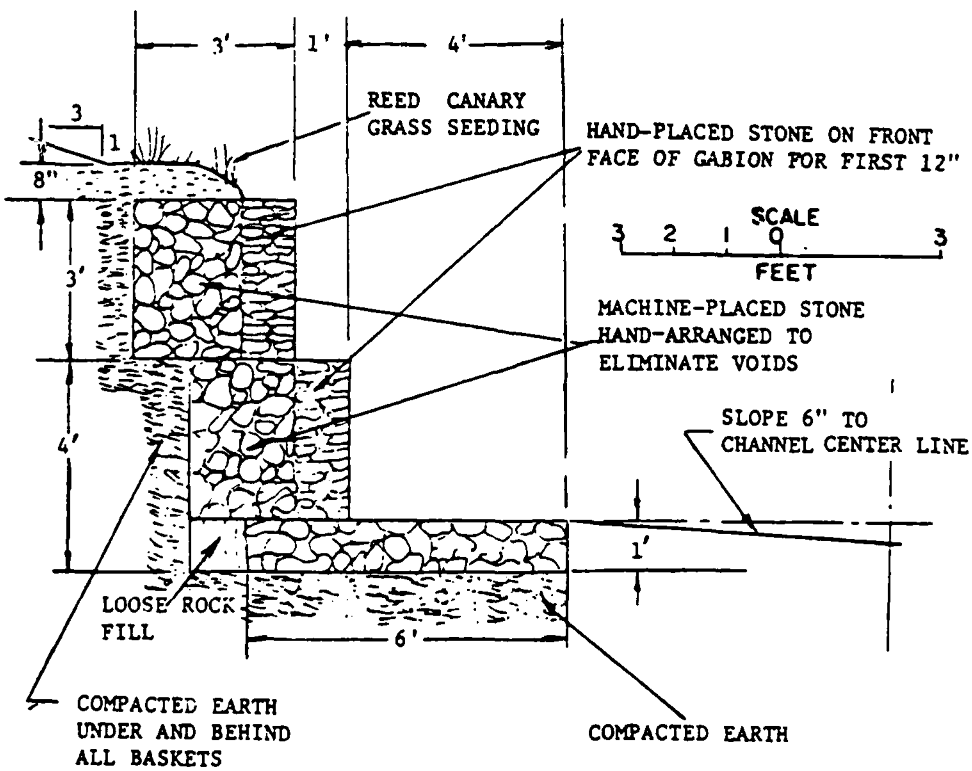

Figure 32. Gabion baskets stacked in stairstep fashion to form a continuous revetment (OCE 1981, Appendix H)

Where there is limited adjacent land or access, e.g., urban areas, gabions require less right-of-way than riprap revetment designs. The amount of stone required for gabions is one-third to one-half that required for riprap at the same location, and the stones are smaller. In comparison to concrete, gabions are far cheaper and, as cited above, gabion works are not very vulnerable to shifts in the underlying banks, although some maintenance is required for large bank shifts (Burroughs 1979).

149. Gabion works may be used as toe protection only, or stacked to form grade control structures (Figure 33) (Maccaferri 1981). When gabions are used for toe protection, the upper bank may be graded and planted in grasses, or the upper bank may simply be backfilled behind the gabions. Gabions may be used in enlarged channels to define a low-flow channel as well as to provide toe protection (OCE 1981, Main Report). The USAED, Omaha, used gabions to realign a channel for urban development. This design incorporated gabion drop structures for grade control (OCE 1981, Appendix H).

Figure 33. Gabions used for grade control
(from Linder 1976)

150. Environmental considerations. Gabion works allow for revegetation and exchange of water between the bank and the channel. Because gabion works require less of the streambank for placement (i.e.,

may be placed on steeper slopes), more streambank vegetation is preserved. Unvegetated gabions are similar in appearance to masonry work, which may be aesthetically pleasing in some settings. The steep slopes on which gabions are used may hinder wildlife access. Gabions are used to enhance trout habitat during low-flow conditions. Artificial streambank overhangs constructed of gabions project out over the channel approximately 2 ft to provide a hiding, resting, and spawning habitat. Minimum depth and velocity conditions are maintained through use of gabion barriers, deflectors, spur dams, and artificial boulders used to control flows (Cooper and Wesche 1976).

Limitations

151. The major problem with gabion works is basket failure. The wire baskets may be ruptured by heavy debris (ice, rocks), vandalized, or corroded by acidic streamflows (Burroughs 1979, Keown et al. 1977). Gabions may be sprayed with gunite after installation as protection against vandalism. Failed baskets may be hazardous to recreationists, particularly canoeists and tubers.

Performance

152. Gabion works have been used with excellent results in toe protection and grade control designs (Burroughs 1979; Saunders and Grace 1981). Nunnally and Shields (1984) discuss the use of gabions to construct aquatic habitat and grade control structures for flood control channels and give information regarding performance.

Costs

153. The cost of gabion works varies with the cost of the unskilled labor, type of upper bank treatment, and availability of rock or stone. Section 32 gabion demonstration project costs (1984 dollars) are tabulated below (OCE 1981, Main Report and Appendixes G and H).

Design	Cost per Foot of Bank Protected
Gabion at toe, grass on upper bank, and gabion grade control structures	$37-140
Gabion mattress with upper bank vegetation	$119-234
Gabion dike at toe and backfilled to the slope	$572

Fencing and Buffer Strips

Description

154. Concept. Cultivation, livestock grazing, and other agricultural activities can result in severe erosion along small streams. In some cases, erosion can be decreased by development of vegetative buffer strips. Fences may be constructed roughly parallel to the channel to exclude livestock and farm machinery from the riparian zone, thus allowing a buffer strip of riparian vegetation to develop (Figure 34) (Lines, Carlson, and Corthell 1979). When the riparian area is completely denuded, the buffer strip may be seeded after fencing with a grass-legume mixture to prevent further erosion. Plant species normally found along streams, such as willows, alders, cattails, and blackberry and snowberry vines, will invade the stabilized buffer strip. Planting of these species may be desirable if natural invasion is not rapid (Lines, Carlson, and Corthell 1979; Winegar 1977).

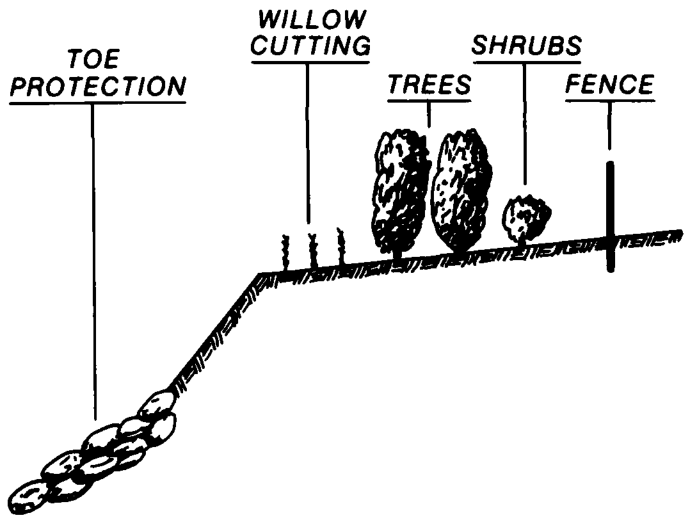

Figure 34. Fencing and buffer strip design (adapted from SCS 1978a)

155. Environmental considerations. Buffer strips increase terrestrial habitat diversity by restoring the valuable riparian zone. Fences may be designed to allow passage of large wildlife, e.g., deer or antelope, but not livestock (Yoakum et al. 1980). Aquatic habitat is

improved because the buffer strips intercept a portion of the sediment load, which is sometimes extremely high in agricultural areas where buffers are used. Buffer strips may therefore reduce stream turbidity and sediment concentrations (Winegar 1977). The aesthetics of the stream are improved because vegetated banks are more desirable than eroding banks.

Limitations

156. Use of buffer strips is limited to erosion situations that can be corrected simply by establishment of natural vegetation and sites where lower bank protection is provided. Fences may be damaged or destroyed by overbank floods, livestock, or recreationists (Carlson 1982). Debris may become lodged on fences and vegetation, and this may obstruct flow and increase flood heights. Increased flow obstruction may be allowed for in flow computations using increased values for Manning's n or modified channel cross sections in uniform flow equations. Nunnally and Shields (1984) present a table of published values of Manning's n for small streams with various types of bank vegetation.

Performance

157. Buffer strips have been used successfully by the US Department of Agriculture Soil Conservation Service (SCS) for stabilizing banks of small streams (SCS 1978a). The environmental benefits include improvement of water quality and development of riparian habitat. On an Oregon stream, vegetation within the fenced areas caused a reduction of sediment inflow of between 48 and 79 percent, compared to unfenced reaches (Winegar 1977). Because of the sediment retention, the stream bottom began to build up and the water table rose within the protected reach. The vegetative diversity of the fenced reaches prompted greater use by wildlife (Table 3). Prior to the establishment of the buffer strips (Winegar 1977), there were no beavers and few waterfowl along the stream. After the buffer strips a number of beaver dams appeared, in addition to several waterfowl nesting sites.

Costs

158. Cost data for fencing and buffer strips are unavailable. Major cost elements include acquisition of rights-of-way, placement of

Table 3

Comparison of Wildlife Use of Buffer Strip and Unfenced Channel

(from Winegar 1977)

	Wildlife Observed in 2.5 Miles of Channel with Buffer Strip	Wildlife Observed in 2.5 Miles of Unfenced Channel
Small birds (spp. unidentified)	33	0
Bank swallow	35	2
Cooper's hawk	1	0
Sparrow (4 spp. not separated)	30	20
Frog (2 spp.)	3	0
Hermit thrush	4	0
Redtail hawk	1	0
Great horned owl	1	0
Flicker	1	0
Valley quail (estimate in one covey)	10	0
Spotted sandpiper	2	0
Loggerhead shrike	2	0
Killdeer	2	16
Sage grouse	0	22
Cottontail rabbit	1	0
Jackrabbit	1	2
Least chipmunk	2	5
Beaver (activity, chewing, etc.)	Estimate 2	0
Mole (mounds, burrows)	Estimate 20	0
Mule deer (tracks only)	Several	0
Coyote	Tracks only	1
Rattlesnake	0	6
Fence lizard	0	1

fences, and maintenance, e.g., removal of debris from fences (Lines, Carlson, and Corthell 1979; Winegar 1977).

Fence Retards

Description

159. Concept. Board or wire fences may be used on small streams as flow retardance devices (Figure 35). Reduced flow velocities induce sedimentation, and vegetation is quickly established. Fences may be

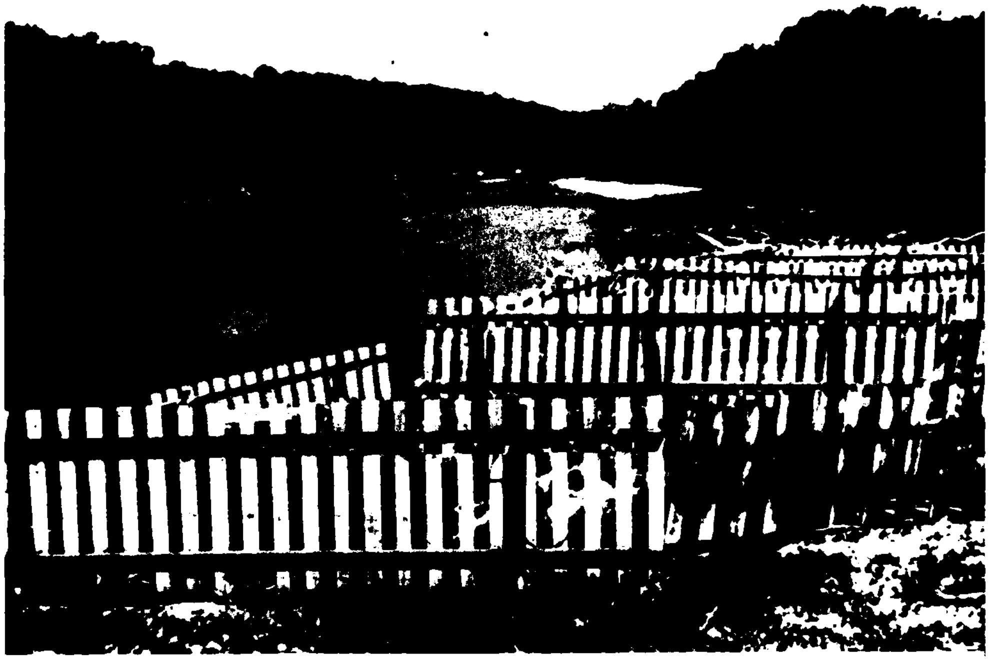

Figure 35. Fence retard

placed longitudinally along the streambank or transversely as dike structures. Longitudinal fences usually have perpendicular tiebacks at intervals as reinforcement and deterrents to flanking (OCE 1981, Main Report and Appendix F; McBride and Strahan 1983). In rivers subject to freezing, retards constructed parallel to the bank are less subject to ice damage than transverse structures. The fences prevent scouring and erosion on the upper bank. If oversteepening of the bank is a problem, some form of toe protection is also required.

160. Environmental considerations. Fence retards promote sedimentation and invasion by species such as willows. The stabilized bank increases access to the channel for wildlife. Visually prominent fences may have adverse aesthetic impacts; however, revegetation will subsequently improve the appearance of the eroding bank and may obscure the fence.

Limitations

161. Board fences protect the upper bank only. Use is limited to channels where toe degradation and bank undercutting are not problems or where toe protection is incorporated into the design. Model tests have

shown that toe scour is significant for longitudinal retards, and failure will result if the posts are not installed deeper than the scour depths (OCE 1981). Fences are more easily damaged by ice and tow traffic than are stone structures.

Performance

162. Board fence retards are effective in promoting establishment of vegetation on the upper bank. Minor scour problems have been noted at some structures, but the fences do provide effective bank protection (OCE 1981).

Costs

163. Costs for fence retards vary with site characteristics. For the Section 32 Program demonstration sites, costs ranged from $24 to $379 per foot of bank line protected (1984 dollars) (OCE 1981, Main Report).

Hard Points

Description

164. Concept. Hard points are spurs of rock or stone that extend from the bank into the stream to stabilize the streambank. They have been used at numerous locations along the Missouri River. Somewhat smaller structures were used at a Section 32 Program demonstration site on the Allegheny River to protect the bank from ice floes. The hard point has two components, the extension into the stream and the root that is buried landward from the bank (Figure 36). The root is commonly as long as the extension into the stream. Recommended minimum length on rivers such as the Missouri is 100 ft, with a 50-ft root and 50-ft riverward extension (OCE 1981, Appendix E).

165. The crown at the riverward end is constructed to the normal water surface elevation. The hard point crest slopes upward from the riverward end to 5 ft above the normal water surface elevation at the landward end. Crown width varies up to a 10-ft maximum and is inversely proportional to water depth. On the Missouri River, the lower toe zone below the normal water surface is constructed of 500-lb (maximum) stone or low-grade material, and the remaining upper portion and root are

Figure 36. Hard point system (from OCE 1981, Appendix E)

built with 200-lb (maximum) stone (OCE 1981, Appendix E).

166. Hard points are used on the Missouri River where possible in lieu of revetment systems. For each foot of hard point spur placed riverward of the bank, approximately 5 ft of bank line is protected from extensive erosion. For example, a 50-ft riverward spur protects 250 ft of bank. Series of two to six hard points are used on straight or convex-shaped bank lines where stream flow lines are parallel to the bank line, but are not used on actively eroding banks experiencing direct attack by the stream. Erosion between the hard point structures continues until an equilibrium is established, and thus the resultant bank line is scalloped (OCE 1981, Appendix E).

167. Environmental considerations. Hard points have desirable effects on terrestrial and aquatic habitats, aesthetics, and recreation. Aquatic habitat diversity is increased by hard points. Protected slackwater areas develop between hard point structures, and scour holes develop at the riverward ends, providing deep-water habitat. The stone provides benthic habitat for attachment-type organisms, and sediment deposition between hard points provides habitat for burrowing types.

Disturbance to terrestrial habitats is minimized since less upper bank clearing is required than for revetments (e.g., continuous or tiebacks for reinforced revetments). Areas disturbed by clearing and excavation for root placement quickly revert to preconstruction conditions. Sedimentation and natural invasion eventually result in revegetation of the hard point crown and upper bank; however, more immediate results occur if a vegetation plan is included in the design (Figure 37) (Engineering Consultants, Inc. 1978). Vegetation can disguise the structural components altogether. Hard points increase access to the channel for recreation purposes since they may be used to launch and moor boats and thus allow access to upstream and downstream areas (Figure 38).

168. Hard points are not suitable for rapidly eroding banks. Utilization of hard points is restricted to areas with normal water depths no greater than 10 feet along straight or convex bank lines where stream flow lines are parallel to bank lines. Since some erosion continues to occur between them until an equilibrium condition is reached, hard points are inappropriate for critical locations where no further erosion is acceptable (OCE 1981, Appendix E).

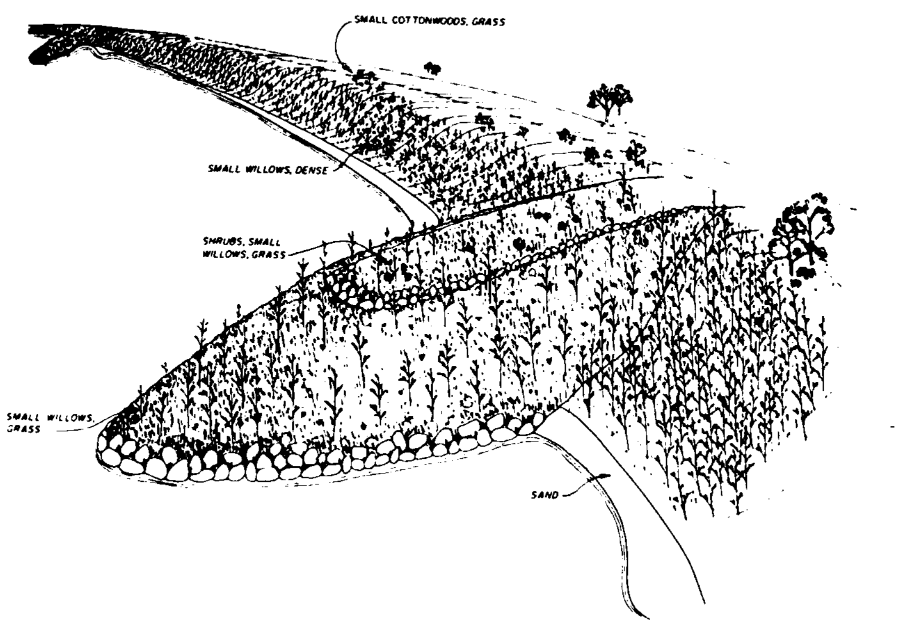

Figure 37. Vegetative plan for a hard point
(from Engineering Consultants, Inc. 1978)

Figure 38. Hard point used to shelter pier and boat launch; note invasion of vegetation (photo courtesy of USAED, Omaha)

Performance

169. Hard points are effective for reducing streambank erosion with a minimum of upper bank disturbance. Aquatic habitat diversity is increased with scouring at the riverward end of the structure and slackwater (reduced velocities) habitat between adjacent structures. Burress, Krieger, and Pennington (1982) conducted a pilot study of fish and benthic macroinvertebrate habitats at channel and streambank stabilization structures on the upper Missouri River. Only three hard point structures were sampled. Fish abundance and diversity was less than at other streambank protection structures, possibly as a result of the relatively small habitat area sampled. Abundance of benthic macroinvertebrates at the hard point structures was greater than natural banks, but less than at other structures. Benthic abundance (number of organism/square foot) for the structures and adjacent stabilized substrates is given in Table 4.

Costs

170. On the Missouri, construction costs were $65-$236/linear foot

Table 4

Benthic Macroinvertebrate Abundance at Various Habitats Along the Upper Missouri River (Adapted from Burress, Krieger, and Pennington 1982)

	Benthic Fauna (Sediment-Dwelling or Burrowing Organisms) (organisms/ft^2)	Rock Fauna (Attached to Stone Substrate) (organisms/ft^2)
Hard points	3.7	77
Stone revetment		
Upper bank	6.8	167
Lower bank	1.6	122
Natural bank		
Upper bank	3.5	N/A
Lower bank	9.2	N/A
Stone dike		
Wing (transverse)	49.5	196.5
L-head	73.4	364.5
Earth core dike	7.8	479.6
Backwater chute	12.6	N/A

of structure; bank protection costs were \$10-\$94/foot of bank line protected (1984 dollars) (OCE 1981, Appendix E).

Jetties and Vegetation

Description

171. Concept. Combinations of structures and vegetation have been used for streambank protection along small streams in the Pacific Northwest (Lines, Carlson, and Corthell 1979) (see also sections Fencing and Buffer Strips; Tree Retards, Pendants, and Revetments). In Oregon, rock or gabion jetties are used by the SCS to protect streambanks. Jetties function by deflecting flows away from the streambank on small streams, in the same way hard points and dikes are used on large streams. A

series of jetty structures project into the stream perpendicular to the direction of flow (Figure 39). Willows or other woody vegetation are planted in high densities along the streambank between the structures. A grass-legume mixture is planted to stabilize the bank while the willows become established (Lines, Carlson, and Corthell 1979; SCS 1978b). The reduced velocities between jetty structures induce deposition and sandbar formation between structures. The sandbars then become vegetated.*

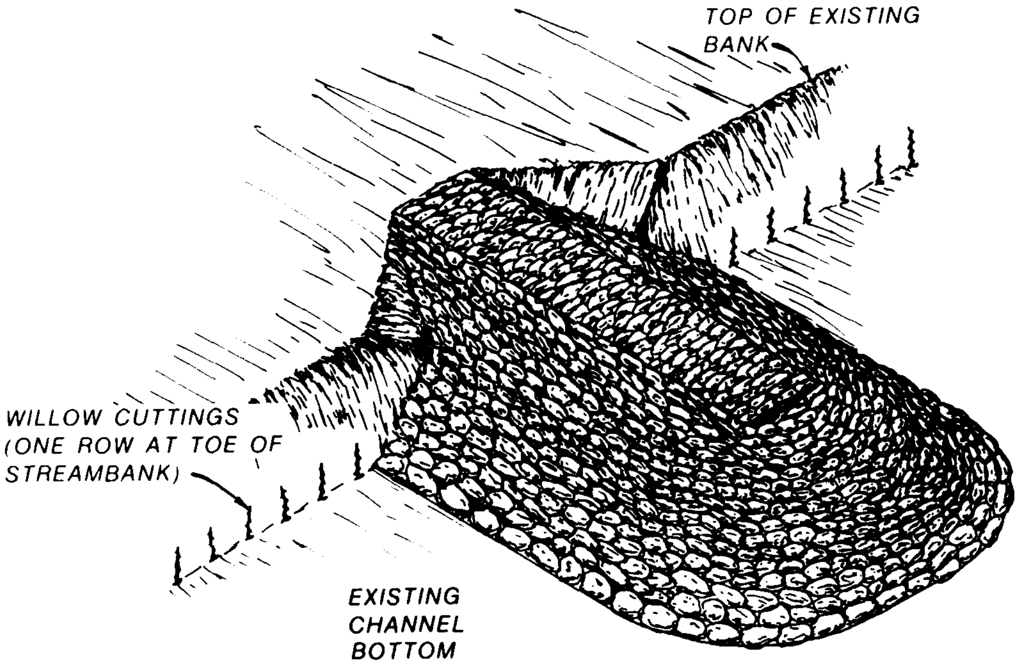

Figure 39. Jetty design for Wallowa County Streambank Protection Project, Oregon (adapted from SCS 1978b)

172. Environmental considerations. Slack-water habitat develops downstream of each jetty structure, increasing aquatic habitat diversity. The grasses and woody vegetation establish riparian habitat along the streambank (Lines, Carlson, and Corthell 1979).

Limitations

173. On streams with high velocities or severe erosion conditions, the jetty and vegetation strategy may require ancillary measures such as structural protection between the jetties.

* Personal Communication, 1983, Mr. Donald L. Stettler, Assistant State Conservation Engineer, SCS, Portland, Oreg.

Performance

174. The jetties and vegetation strategy has been successful on Oregon streams in stabilizing streambanks and establishing riparian vegetation along the stream.

Costs

175. Major cost elements include construction of the jetty structures, seedbed preparation for the grass-legume mixture, and bank preparation for the planting and maintenance of the woody vegetation.

Drop Structures

Description

176. Concept. Drop structures are grade control structures used to control streambank erosion where streambed degradation and bank undercutting occur. Drop structures consist of some type of flow-retarding structure such as a weir and an energy dissipating structure such as baffle piers or a baffle plate downstream of the weir (Figure 40). A protected stilling basin or pool is required below the dissipating structure. Erosive waves produced from flow over the weir are thus broken

Figure 40. Drop structure consisting of a weir and baffle plate (from OCE 1981, Appendix F)

up before entering the downstream channel (Little and Murphey 1982). Drop structures prevent the upstream progression of headcuts by reducing the upstream water surface slope. The increased depth and flattened slope reduce the velocity of erosive flows (Linder 1976, Little and Murphey 1982).

177. Drop structures may be used to reduce flow velocities instead of extensive treatments to prevent erosion caused by fast velocities. The erosive energy of the flow is dissipated at a single location, rather than along the length of the channel (Linder 1976). Construction materials and designs for drop structures vary widely with channel flow and sediment characteristics (Ferrell and Barr 1963, Heede 1966).

178. Environmental considerations. Construction and maintenance of drop structures disturb far less riparian habitat than construction of intermittent or continuous structures along the channel. In many cases, natural revegetation of formerly eroding, denuded banks will occur following placement of a drop structure (Figure 41). Low-flow channels can be designed along the side of weir structures to prevent

Figure 41. Drop structure using baffle piers; note vegetation on bank and minimal use of rock or other structure on the banks (from Linder 1976)

isolation of upstream and downstream pools during low flow. Additional information regarding fish passage at drop structures is provided by Nunnally and Shields (1984).

Limitations

179. Use of drop structures is limited to relatively small channels where bed degradation is the primary cause of streambank erosion. If degradation is proceeding upstream with a headcut, a suitable site for the drop structure is upstream of the headcut preceding enlargement of the channel.

Performance

180. Drop structures used on a range of stream sizes have been successful in stopping bed degradation and bank erosion. When structures are made of gabions and/or riprap, interstitial siltation and resulting vegetation create a more natural appearance (OCE 1981, Appendix F).

Costs

181. Costs for drop structures vary greatly depending on stream characteristics. The costs for the drop structures at three of the Section 32 Program Yazoo basin demonstration sites are given below (1984 dollars) (OCE 1981, Appendix F).

Construction Costs ($1000)	Number of Structures
1008	3
352	1
1064	10

Additional examples of grade control structure costs are given by Nunnally and Shields (1984).

Jacks

Description

182. Concept. Jacks (often called Kellner jacks) are structures used to retard flow and promote growth of vegetation (Figure 42). The structures are joined in units to form jack fields for channel alignment and streambank protection along low-gradient streams. Current velocities are slowed within the jack field, thus causing sediment deposition. Jacks usually are constructed from concrete or steel beams (Myers and Ulmer 1975, Illinois Department of Conservation 1983). Advantages

Figure 42. Kellner jacks placed longitudinally along the bank; note vegetation behind the jack line (photo courtesy of SCS)

of jack fields include ease of construction, minimal site preparation, and flexibility, i.e., the jacks respond to changes in streambed configurations (Shields and Palermo 1982).

183. There are a number of jack configurations, the most common being three beams approximately 15 ft long bolted together at right angles at their midpoints. The three beams form apexes of a triangle, with two legs upstream and the third leg downstream (Myers and Ulmer 1975). Jack fields are constructed by placing assembled jacks in one or more longitudinal rows in the streambed and placing lateral lines of jacks used as tiebacks at intervals of 75 to 150 ft. Spacing of tiebacks depends on site factors, such as degree of bank curvature. Steel cables are strung from jack to jack. The cables strengthen the jack field and also catch debris, which promotes additional sediment deposition. Cables are anchored to deadmen on the bank to prevent flanking. Anchors are set in the channel bottom, and timber or steel pilings are

placed at intervals along the jack line. Jack fields extend upstream and downstream a sufficient distance to establish an alignment pattern (Myers and Ulmer 1975; OCE 1981, Appendix F).

184. Environmental considerations. Jack fields cause deposition of sediment that forms a suitable substrate for dense growths of willows, cottonwoods, and underbrush. This vegetation measurably improves the stability of the bank and restores the riparian nature of eroded banks. Although jack fields have an unappealing, unnatural appearance, they eventually may be overgrown by vegetation and concealed.

Limitations

185. Jack fields have been designed for streams with maximum near-bank depths of less than 12 ft and may be unstable in deeper streams. Jacks are unsuitable for streams with low sediment loads because insufficient deposition occurs. High-velocity flows can also damage the structures by lifting the jacks from the streambed (Myers and Ulmer 1975; OCE 1981, Appendix F).

Performance

186. Jack fields have performed successfully to stabilize streambanks and force flows to the center of the channel. Three existing projects evaluated during the Section 32 Program were performing adequately, with vegetation becoming well established in sediment deposits. However, some damage occurred due to floating ice and debris during high flows, and the jacks were ineffective in high-velocity flows (OCE 1981, Main Report and Appendix G).

Costs

187. Costs of jack fields per foot of bank protected ranged from $20 to $94 (1984 dollars) for those projects evaluated during the Section 32 Program (OCE 1981, Main Report).

Earth Core Dikes

Description

188. Concept. Earth core dikes are river training dikes constructed with a sand and earth core and a thin layer of stone on the

upstream face (Figure 43). A stone toe is also embedded upstream. Earth core dikes have been used on large streams, and the material presented here is from a Section 32 Program demonstration site on the Missouri River. The structure functions by deflecting high-velocity flows away from erodible banks. Earth core dikes are built on top of existing sandbars, reducing the amount of fill required. To decrease the chance of flanking, a root or landward extension of the structure is placed in an excavated trench (OCE 1981, Appendix E).

189. The Missouri River earth core dike was 1500 ft long and protected 4000 ft of bank line downstream of the structure. The crown of the dike was constructed to 5 ft above normal water surface. A low-elevation notch was included in the design to allow flow through the structure in order to prevent sedimentation downstream and thus maintain aquatic habitat. The earthen part of the dike was planted with woody and herbaceous vegetation.

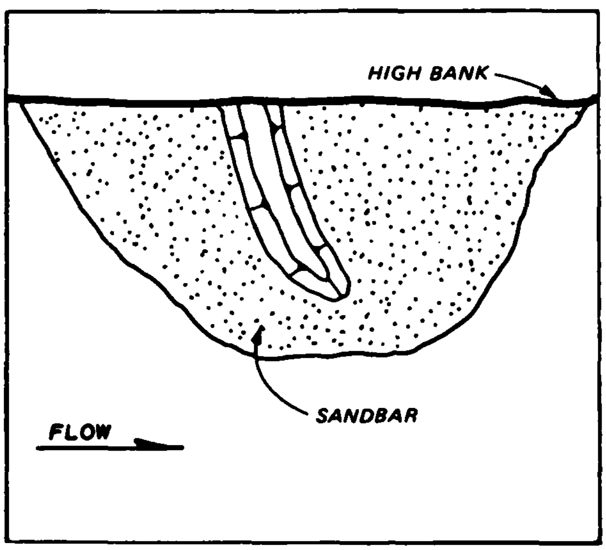

Figure 43. Earth core dike (from US Fish and Wildlife Service 1980)

190. Environmental considerations. Earth core dikes require only limited upper bank clearing for root placement, and the excavated area rapidly revegetates through natural invasion. The earth core dike lends

itself to vegetative treatment. The Missouri River dike was planted with 2600 woody plantings, e.g., willow, cottonwood, and ash (Figure 44), and extensive areas of reed canarygrass. Vegetation on the structure allows it to blend with the surroundings (US Fish and Wildlife Service 1980). The notch in the dike provides sufficient flow during high water to prevent sedimentation, and thus preserves slack-water habitat with direct connection to the main channel. This backwater area is extremely important as a nursery area for numerous species of fish and is critical to the survival of some species. This type of aquatic habitat is often scarce in large, stabilized river systems.

Figure 44. Vegetation on earth core dike

Limitations

191. The construction of an earth core dike requires a greater concentration of equipment than other bank protection structures, and adequate site access and a nearby source of fill material are required. The Section 32 Program recommended use of earth core dikes only where the nearshore area is shallow (7 ft or less at normal stage), due to the increased fill required for deeper channels (OCE 1981, Appendix E).

Performance

192. The earth core dike was effective in eliminating erosion downstream of the structure. The notch placed in the structure functioned well to enhance the backwater area. The vegetation program was quite successful, making the structure appear much like a vegetated sandbar (OCE 1981, Appendix E). Benthic macroinvertebrate habitat is improved by the earth core dike due to stabilization of adjacent substrates for burrowing forms and the addition of stone for attachment forms. Abundance of benthos at the Missouri site was greater than at hard points, stone revetments, and natural bank sites, but significantly less than for dike structures (see Table 4). The backwater area was utilized by fish as a nursery area and for protection during high water (Burress, Krieger, and Pennington 1982).

Costs

193. The Missouri River earth core dike cost approximately $82 per foot of bank line protected (1984 dollars). (The 1500-ft structure protected 4000 ft of bank line.) The dike was therefore quite cost effective, even though the cost per foot of structure is greater than for other structures (OCE 1981, Appendix E).

PART V: MAINTENANCE, CONSTRUCTION, AND MANAGEMENT PRACTICES

194. The structural design selected for a given site is the most direct determinant of the ultimate environmental effect of a streambank protection design. However, environmental objectives may also be promoted during construction and maintenance. This part discusses practices that may be used to minimize construction effects and enhance habitat and aesthetic values through maintenance activities.

Selective Clearing

Description

195. Concept. During maintenance of streambank protective structures, wildlife habitat can be enhanced by preservation of vegetation that invades the structure (Figure 45). However, maintenance practices often require removal of all vegetation (a) to protect the structure from damage by roots and other vegetative structures (e.g., vines), and (b) to allow aerial or ground-level visual inspection of the structures. Large trees can be uprooted by the current at high flows, leaving holes

Figure 45. Woody vegetation and vine growth on riprap revetment

in the rock blanket. The holes are then subject to scour and rapid enlargement. Vines are capable of damaging the revetment if debris becomes tangled in the vines during floods and causes large clumps to be uprooted (Forbes et al. 1976). Therefore, vegetation normally is removed from revetments by mechanical clearing or application of herbicides prior to inspection.

196. Maintenance procedures that leave a portion of the vegetation intact preserve riparian habitat. Selective clearing consists of manual clearing and removal of vegetation that is detrimental to the integrity of the revetment; vegetation that increases the stability of the revetment or does not reduce protective capability is allowed to remain. Preparing specifications for selective clearing requires knowledge of plants that normally invade revetments on a stream reach, successional changes occurring on the revetment, and the adaptability of certain plants to revetment conditions. Size and density of vegetation are often used as the selection criteria. Selective clearing along the Willamette River has been utilized since broadcast spraying of herbicides was discontinued. The clearing criteria call for the removal of woody growth that is 2 in. or more in diameter or 6 ft or more in height and the removal of all vines (USAED, Portland 1975).

197. Environmental considerations. Selective clearing results in the establishment or preservation of riparian habitat while protecting the integrity of the revetment. Preservation of grasses, small shrubs, and trees gives a more natural appearance to the streambank.

Limitations

198. Selective clearing is applicable only where revetments normally support valuable vegetation that is routinely cleared or sprayed. Plant growth must be accessible to workers. Since bank protection works are often maintained by local sponsors, implementation of this concept by the CE is limited to CE-maintained revetments or situations where interagency coordination and cooperation are good.

Performance

199. Selective clearing procedures have been utilized on Willamette River revetments. Hynson et al. (1984) discuss selective

vegetation clearing for levees, and some of this information may apply to bank protection works.

Costs

200. Costs for complete clearing of revetment are $2.73 per linear foot. Selective clearing costs are estimated at $2.91 per foot (1984 dollars). The additional cost is due to increased "in-house" planning, supervision, and administration.* Niering (1958) compiled a range of costs for selective vegetation management on rights-of-way using herbicides and found overall prices to range from $97 to $945 per acre (1984 dollars).

Revetment Maintenance Categories

Description

201. Revetment maintenance techniques can be adjusted to preserve some of the riparian vegetation growing on revetments. Revetments along a stream may be classified based on engineering and adjacent land use factors and maintained accordingly (Figure 46, Table 5). Some revetments require complete clearing while others may be allowed to overgrow. Intermediate sites may be candidates for selective clearing.

202. Revetments along the Willamette have been classified based on (a) area protected (potential economic loss, loss of life) and (b) likelihood of failure (i.e., the erosional setting). Different levels of maintenance are applied to each revetment category, and separate vegetative restrictions and revetment encroachment standards may be developed. Vegetative restrictions limit the size, kinds, and density of vegetation permitted on the revetment (USAED, Portland 1980). Vegetative management on the Willamette revetments emphasizes preservation of unique vegetative assemblages rather than common upland assemblages.**

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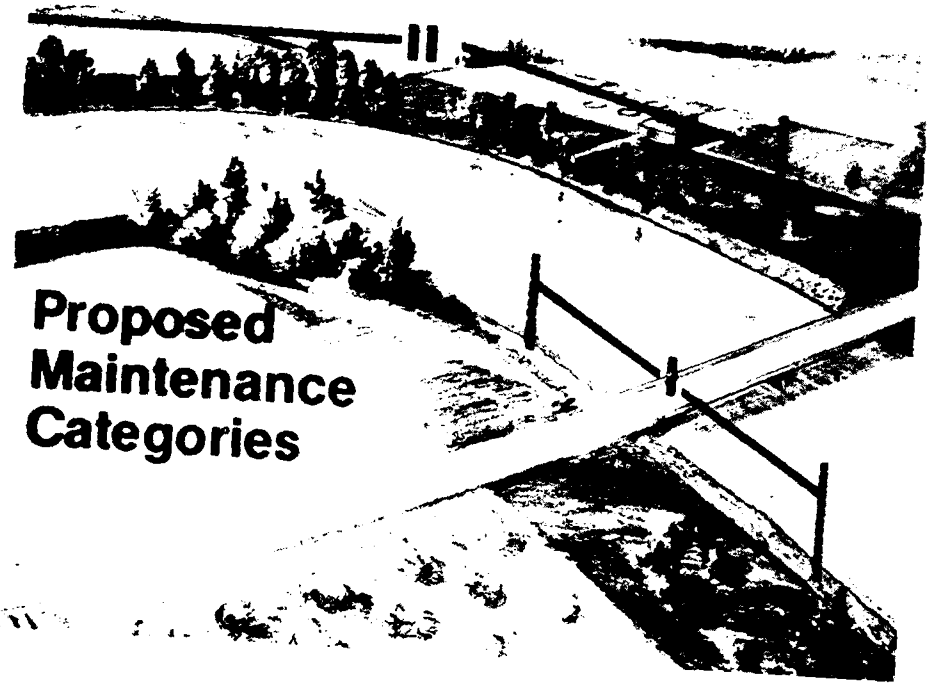
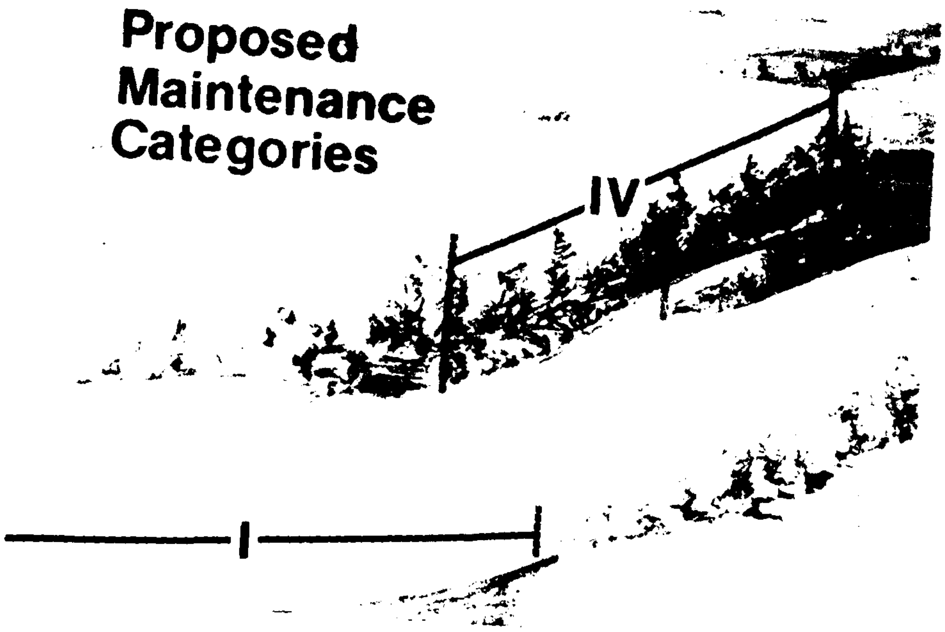
* Personal Communication, 1983, Mr. Jim Reese, USAED, Portland.
** Personal Communication, 1983, Mr. Thomas Morse, USAED, Portland.



a. Categories I and II



b. Categories I, III, and IV

Figure 46. Examples of revetment maintenance categories (see Table 5)

AD-A150 660 ENVIRONMENTAL AND WATER QUALITY OPERATIONAL STUDIES ENVIRONMENTAL FEATURE..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR.. 2/2

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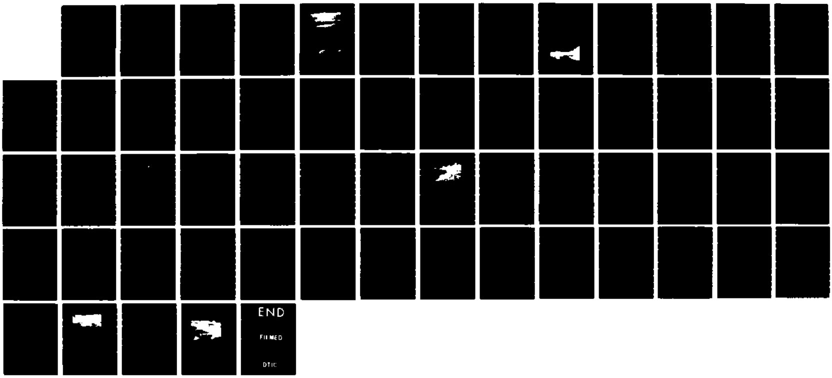

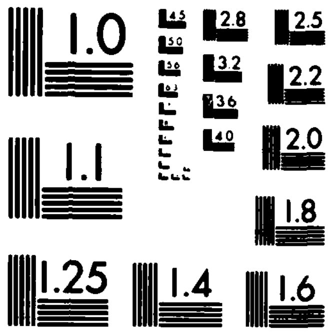
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0

Table 5

Vegetation Maintenance Categories and Criteria for Existing Revetments

Category	Area Protected	Environmental Setting	Vegetative Restrictions
I (High Value--High Risk)	Critical public and private structures (bridges, roads, homes).	Revetment is under attack from the river. Structure too close (0-75 ft) for emergency repairs if revetment fails.	No vegetation to hinder inspection or impact the structural integrity of the revetment is allowed.
II (High Value--Low Risk)	Economically significant structural improvements.	Revetment is under attack. Structures are set back 150 ft or more from the crown of the revetment, giving sufficient time for emergency repairs.	(1) No vegetation that prohibits aerial inspection. (2) Sod cover of grasses and herbaceous plants, scattered clumps of low-growing (<3-ft high) shrubs and individual trees of diameter breast high (DBH) less than 6 in. and 25 ft in height.
III (Low Value--Low Risk)	Agricultural lands, parks, and other natural areas.	Revetment under attack from river.	(1) No vegetation that prohibits ground inspection. (2) Sod cover of grasses and herbaceous plants; scattered clumps of shrubs and trees DBH of less than 10 in. and 40 ft in height.

(Continued)

Table 5. (Concluded)

Category	Area Protected	Environmental Setting	Vegetative Restrictions
IV (Low Value--No Risk)		Revetment protected from direct attack by channel change or gravel bar formation that has occurred since construction.	None; vegetation is allowed to develop.

Revetment encroachment standards limit how close to the revetment the structures on adjacent land (farm buildings, residences, commercial establishments) can be located. For all maintenance categories, these standards allow no permanent structural encroachment. If, on annual inspection, conditions have changed at the revetment, the revetment classification can be altered accordingly. Maintenance categories for Willamette River revetments used by the Portland District are summarized in Table 5 (USAED, Portland 1980).

Limitations

203. Use of maintenance categories requires greater in-house planning and administration than complete clearing or selective clearing. No significant problems or limitations were encountered with implementation of revetment maintenance categories on the Williamette.*

Performance

204. The system has not been in use long enough to be adequately evaluated.*

Costs

205. The cost of using the vegetation maintenance categories has not been determined due to the short time the system has been used.* Costs for selective clearing are slightly higher than for complete clearing (see Costs, Selective Clearing).

Revegetation of Riprap

Description

206. Concept. Stone riprap or other bank protection material is often used as protection for engineering structures, e.g., spillway exit channel slopes. After placement, natural vegetation from adjacent stands or from windblown or waterborne seed often invades sediment deposits in the bank protection materials (Figure 47) (USAED, Mobile 1982a, Bierly and Associates 1980). Maintenance practices often require removal of all vegetation to ensure the integrity of riprap structures. It is

* Personal Communication, 1982, Mr. Thomas Morse, USAED, Portland.

Figure 47. Vegetative growth on riprap

desirable to allow some vegetation on riprap because it provides limited wildlife habitat and makes the structure appear more natural.

207. Levee projects sometimes incorporate vegetation plans for riprap-protected slopes (Figure 48). These projects provide guidance in developing plans for riprap vegetation (USAED, Seattle 1978).

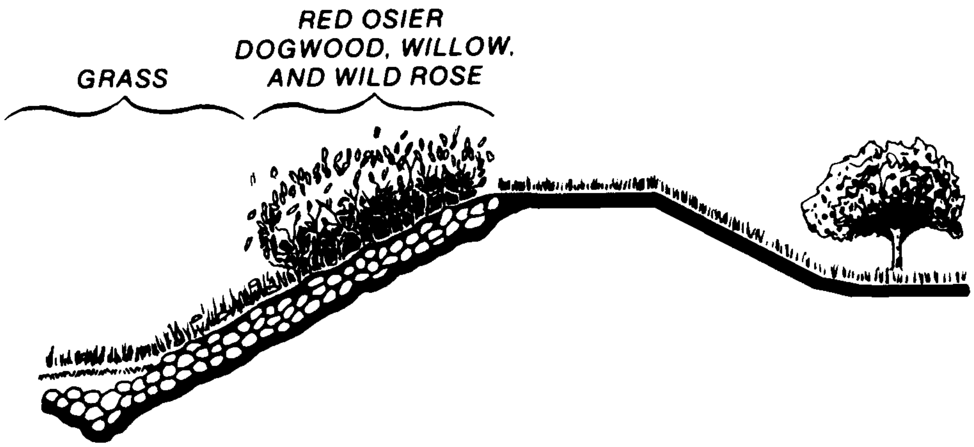

Figure 48. Vegetation plan for riprap on a levee
(adapted from USAED, Seattle 1978)

208. Deciding which structures or portions of structures should be allowed to vegetate should be based on consideration of the damage to the structure that might occur. The Mobile and Nashville Districts developed a policy for vegetation on riprap along the Tennessee-Tombigbee Waterway. Riprap revetments were classified as either critical or noncritical protection. Critical areas are defined as those areas which are main damming surfaces. Vegetation is not allowed on these surfaces because of possible seepage paths opened by root systems, potential damage to the filter fabric or filter layers caused by root growth, and impairment of visual and instrument inspection of slope stability.

209. Examples of noncritical areas are spillway exit channel slopes, downstream lock approach channel slopes, and the riprap located at minimum-flow structures and grade stabilization structures. Generally, any plants or grasses are allowed that will not clog or puncture the filter cloth or displace the riprap. For noncritical surfaces, the Mobile District originally proposed limiting vegetation to small, shallow-rooted shrubs and trees with trunk diameters of 3 in. or less and with density that would allow visual inspection (USAED, Mobile 1982a). After inspection of test sites planted with woody species, it was recommended that the size and density limitations be deleted. The test sites and other vegetated riprap slopes had substantial growths of woody vegetation without any evidence of damage to the structure (USAED, Mobile 1982b). Therefore, on the noncritical surfaces the growth of vegetation will not be controlled. The first 5 years of project operation will be used as an observation period, after which the policy regarding vegetation allowed on riprap will be reviewed (USAED, Nashville 1982).

210. Environmental considerations. Allowing small vegetation to establish and remain on riprap can improve visual appearance and provide limited amounts of riparian habitat. Habitat value for birds and other small wildlife species can be substantially improved.

Limitations

211. Revegetation of riprap will require inspection and maintenance to remove dead vegetation and to check for scour or other damage caused by vegetative structures.

Performance

212. Tests of revegetation of riprap were undertaken prior to establishment of the revegetation policies for the Tennessee-Tombigbee Waterway. Trees were planted at two sites to determine the ability of vegetation to become established on riprap and to determine the effects of vegetation on the structure, e.g., puncture of filter cloth by roots. Two riprap banks (one with filter cloth and one without) were planted with various woody species. The trees were planted in gaps in the riprap blanket; some stones were displaced to provide adequate plant area, and a mixture of soil and fertilizer was added to provide a growing medium. The root balls of the trees were placed in the soil mixture and staked (USAED, Mobile 1982b).

213. The plantings were inspected 16 months later. Numerous additional trees had become established through windblown or waterborne means. The two test sites had 70 and 90 percent survival rates. The site with the lower survival rate showed evidence that the trees had been subjected to flooding and river currents not experienced at the other site. A suitable growth medium, such as the soil mixture used to plant the root balls, was judged necessary for success of the plantings. The trees did not displace the riprap as they became larger. Trees with 6- to 10-in.-diam trunks were growing on the test site. The trees showed radical trunk shape changes at the rock line to conform with odd-shaped gaps between rocks. The effect on the integrity of the filter cloth was not determined because the root systems had not developed sufficiently to penetrate the cloth. It was the opinion of the Mobile District study team that roots open holes slowly as they expand and simply plug the hole that they have made. The overturning of trees by the wind and subsequent scour of holes in the riprap was judged unlikely. Observation of established vegetation indicated that the root systems were not upturned by wind. The trees were thought to snap off near ground level (USAED, Mobile 1982b).

Costs

214. No cost data are presently available. Major cost components are site preparation, plant procurement (commercial species or locally

available native species), and inspection and maintenance costs.

Construction Scheduling

Description

215. Construction of streambank protection structures often requires particular hydraulic and weather conditions. When vegetative treatments are involved, planting success can be heavily influenced by scheduling to take advantage of optimum growing conditions (see paragraphs 121-122). Within these constraints, construction can sometimes be scheduled to reduce interference with recreational use and to avoid sensitive periods for aquatic biota. In some cases, the vast bulk of fishing or boating on a stream occurs during a particular season. Fish spawning and migration occurs during specific times of the year, and construction activities can have much greater deleterious effects during these periods. Critical periods for recreation and fishery resources vary from stream to stream.

Limitations

216. Adjustment of construction scheduling to meet environmental objectives is limited by a number of factors. Most bank protection construction must be done during low or moderate flow to allow bank preparation. Floating plant construction may be hindered by high stages and velocities. Institutional funding schedules sometimes dictate construction schedules.

Performance

217. Conner, Pennington, and Bosley (1983) found larval fish more abundant in most of the five Lower Mississippi River habitats they sampled in May and June than in July and August. Accordingly, they recommended that construction of dikes and revetments not coincide with the peak spawning season and that construction activities be delayed until fall if possible. Currently, most construction on the lower Mississippi is done in the fall. This study did not sample larval fish adjacent to natural caving or eroding banks, and therefore the impact of constructing revetments on these banks during peak spawning seasons cannot be

estimated using their findings. Larval fish abundance and population composition data for revetted banks were similar to data for the main channel. Larval fish were found in greatest abundance in the abandoned channel habitat.

Costs

218. Bank protection costs may be increased if construction is not permitted during periods of optimum construction conditions, or if work must be interrupted tor a period of time. Requirements for irrigation and replanting vegetative treatments may be reduced by appropriate scheduling.

Floating Plant Construction

Description

219. Concept. Construction of streambank protection works requires heavy equipment access to the bank for clearing, slope preparation, and stone placement. Unstable or excessively high banks make land-based construction difficult and, in some cases, hazardous. Use of a floating plant for construction requires that barge loading and staging areas be available near the construction site (Figure 49). Floating

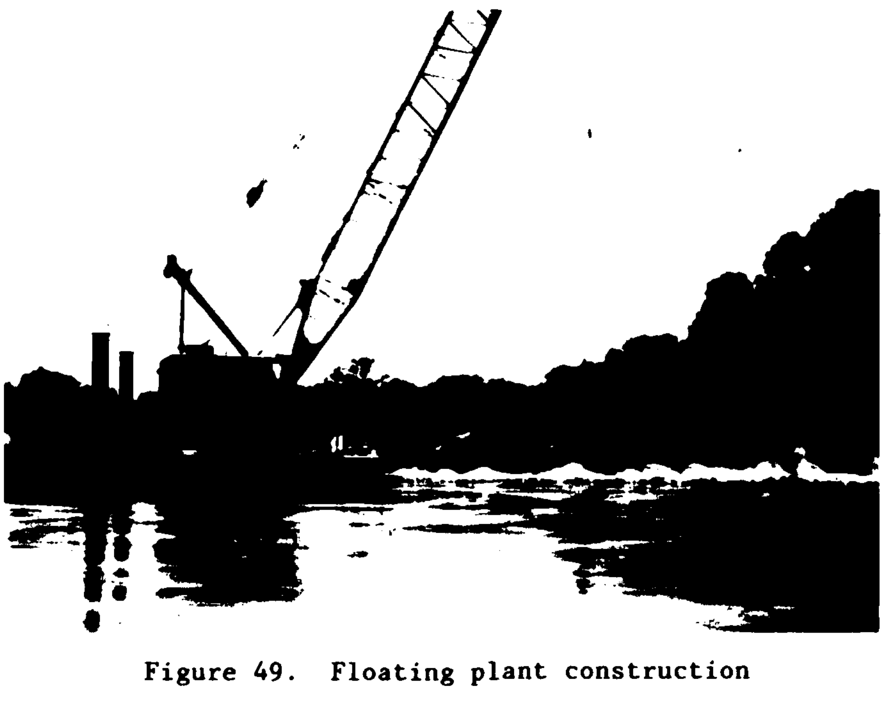

Figure 49. Floating plant construction

plant construction has been used to implement the following designs: (a) windrow revetments, due to the high and unsafe caving banks on which this design is normally used, (b) composite revetments, (c) reinforced revetments where the banks are excessively high and/or unstable, and (d) riprap or articulated concrete mattress revetments (OCE 1981, Main Report and Appendix E; Moore 1972).

220. Environmental considerations. Floating plant construction results in minimal disturbance of the upper bank by eliminating the need for haul roads and upper bank clearing (OCE 1981, Main Report). Construction from a floating plant provides adequate access with reduced environmental effects compared to land-based construction. The limited clearing minimizes the loss of agricultural lands and valuable riparian and floodplain habitat.

Limitations

221. Floating plant construction is infeasible in streams too small for navigation. For these streams, performing all or part of the work using equipment based within the stream channel can be considered. If only one side of the channel supports significant vegetation, in some cases it may be possible to perform construction from the unvegetated bank or temporary berm placed in the channel. Staging areas and material storage areas must be available near the project site.

Performance

222. Floating plants have been used successfully on the Missouri, lower Mississippi, and Sacramento Rivers for construction of continuous type protection, i.e., revetments.

Costs

223. The cost for floating plant construction is greater or less than that for land-based construction, depending on a number of factors including design and availability of staging areas.

Stream Corridor Management

Description

224. Concept. Streambank erosion is a natural fluvial process,

occurring in a systemic manner through a river basin or stream reach. Most streambank protection strategies are localized to particular sites. Stream corridor management, on the other hand, attempts to effect streambank protection and simultaneously achieve environmental objectives through management of basinwide factors. Components of stream corridor management include: (a) keeping the channel free of significant flow obstructions while maintaining the natural fluvial and riparian character of the stream, (b) maintaining top bank vegetation, (c) managing overbank access and traffic, (d) controlling farming practices, and (e) managing overbank runoff (Lines, Carlson, and Corthell 1979; Klingeman and Bradley 1976).

225. Maintenance of stream character. Maintaining the fluvial and riparian characteristics of a stream is possible if certain reaches of the stream are allowed to meander within limits. These unstabilized reaches may be located some distance from streambank protection structures to avoid possible damage (Lines, Carlson, and Corthell 1979; Klingeman and Bradley 1976). Construction near the channel along unstabilized meandering reaches is rigidly controlled.

226. Top bank management. Streambank protection is enhanced if the top bank zone is covered by a buffer strip of vegetation. Retention of woody and herbaceous vegetation adjacent to the bank is an effective means of preventing bank erosion (McBride and Strahan 1983). Surface runoff is slowed and infiltration is increased, reducing bank erosion due to overbank flow from upland areas. Vegetation also increases resistance of the banks to other types of erosion, as described in Part IV, Vegetation section (Klingeman and Bradley 1976).

227. Management of overbank access and traffic. Damage to the top and face of the bank sometimes results from human and animal traffic associated with channel access. Use of trails and paths damages vegetation and causes soil to be dislodged, and surface runoff concentrates in the trails and paths (Lines, Carlson, and Corthell 1979; Klingeman and Bradley 1976). Traffic can be excluded from eroding areas and/or directed to protected access points.

228. Farming practices. Farming interests adjoining streambanks

susceptible to erosion can adjust their methods so as not to contribute to erosion. A buffer strip of natural woody vegetation may be preserved between cultivated crops and the channel. Irrigation of fields immediately adjacent to the channel should be done in such a way as to ensure that the bank does not become saturated during periods of low stage (Klingeman 1979).

229. Management of overbank runoff. Adequate soil conservation practices reduce surface runoff and prevent formation of gullies that can intersect and interfere with the stability of a streambank. Use of these practices throughout a small basin or stream corridor can reduce flood peaks and runoff volumes (Klingeman and Bradley 1976).

230. Environmental considerations. Stream corridor management is a preventive approach to protect streambanks. These procedures result in preservation of riparian habitats. Limited channel migration ensures the presence and diversity of aquatic habitats found in unaltered streams. These habitats, such as gravel substrate used for anadromous fish spawning, may be critical to species survival (Shaeffter, Jones, and Karlton 1982).

Limitations

231. The CE has limited authority to control or influence land use. However, stream corridor management may be instituted with the cooperation of local sponsors and other government agencies. Stream corridor management works best for small streams in mostly nonurbanized areas.

Performance

232. Stream corridor management has been implemented on a formalized basis for a large river basin (Willamette) and as a part of the management philosophy for small streams managed by the SCS in Oregon. A formal evaluation of the system and recommendations for changes will be included in the final report of the Willamette River Coordination Committee (WRCC) in 1984.*

Costs

233. Costs of stream corridor management are related to acquisition

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* Personal Communication, 1983, Mr. Thomas Morse, USAED, Portland.

of land within a meander belt, acquisition of land for a buffer strip, and implementation (easements for land conservation, traffic control, and runoff control).

Advisory Groups

Description

234. The CE is often responsible for the design and construction of streambank protection projects, but maintenance of the structures is usually the responsibility of state or local agencies. Other Federal and state agencies have responsibilities for resources (fish and wildlife habitat, land use, etc.), that are affected by streambank protection projects. These agencies are knowledgeable of the ecological resources of specific channels as well as regional trends. It is sometimes desirable to organize experienced personnel from various agencies and groups to provide coordinated input for design, construction, and maintenance. The Portland District formed the WRCC for advice on Willamette River revetments.

235. The WRCC consists of representatives from the CE, SCS, Fish and Wildlife Service, National Marine Fisheries Service, Land Conservation and Development Commission, Oregon Department of State Lands, Oregon Department of Parks, Oregon Water Resources Department, Oregon Department of Environmental Quality, and Oregon State University. The purpose of the committee is to establish engineering and environmental criteria for Willamette River bank protection work. Seven working groups of the WRCC have investigated the following aspects of streambank erosion within the Willamette Basin:*

a. Identify reaches of the Willamette and its tributaries that should be allowed to meander.

b. Develop an early warning system to identify incipient bank erosion so the need for major structural measures can be reduced by early action.

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* Personal Communication, 1983, Mr. Thomas Morse, USAED, Portland.

c. Ensure that construction and regulatory programs for bank protection complement the Willamette Greenway Program.

d. Recommend design changes in bank protection structures for improvement of fish and wildlife habitat.

e. Identify needs for research on causes and nature of bank erosion and impacts of bank management projects.

f. Determine desirable kinds of vegetation to be planted in conjunction with structural treatment for bank protection and for aesthetic and habitat considerations.

g. Determine the geographic area with which the WRCC will be involved and evaluate the effectiveness of the Stream Corridor Management Program.

236. The working groups directed a study that identified and evaluated nonstructural measures for bank stabilization on the Willamette (Klingeman and Bradley 1976), developed planning study criteria for evaluating the habitats of potential construction sites, and developed an aerial photographic inventory of much of the Willamette River basin. A final report of the WRCC investigation and its recommendations is due in 1984.

Limitations

237. Utilization of advisory groups, whether public groups or professional coordination committees, requires deliberate planning by CE Districts so that input is provided in a timely manner. To be productive, input from an advisory group must come before an alternative is chosen or possible alternatives are eliminated. An iterative process between the District and advisory groups is most beneficial; however, since membership of groups can change often, maintaining the participation of a group can be difficult over the protracted period of design, construction, and maintenance. Potential for advisory group success is considerably enhanced if CE personnel make a concerted effort to attract participation by the most qualified personnel from other agencies and if CE personnel take leadership responsibility.

Performance

238. The WRCC is the only advisory group identified during this research project. The work of the WRCC has been instrumental in identifying the primary issues of concern and addressing the effectiveness of

alternative methods of bank protection. The study activities directed by the WRCC (Klingeman and Bradley 1976) further the goal of achieving environmental objectives in streambank protection projects.

Costs

239. Costs for an advisory group are primarily labor costs. The logistics and costs of holding meetings and developing input for District use may be apportioned among member agencies of the group or borne totally by the CE. The group approach results in less duplication of effort in conducting research to address issues that involve the responsibilities of different agencies. In addition, pooling resources such as boats, instruments, vehicles, and personnel is sometimes possible.

PART VI: SUMMARY AND RECOMMENDATIONS

Summary

240. Streambank protection projects can result in a range of positive and adverse environmental effects. Changes in terrestrial and aquatic habitats and aesthetics are the most significant impacts. Adverse impacts can be minimized and positive impacts enhanced through use of environmental features, i.e., structures, procedures, or actions employed in planning, design, construction, or maintenance of a streambank protection project that produce a net increase in environmental benefits.

241. Streambank failure results from both local conditions and basinwide factors. Local, site-specific failures are due to hydraulic (e.g., erosive currents) and geotechnical factors (e.g., bank undercutting due to streambed instability). From a basin or long reach perspective, a specific streambank reach is part of a dynamic fluvial system. A quasi-equilibrium exists between water discharge, sediment discharge, and morphologic variables relating to channel width, depth, and channel slope. Erosion of streambank is balanced by deposition at a streambank downstream of the erosion site. A natural alluvial river cuts into and destroys climax areas on the outside of bends and deposits point bars that are invaded by flood-tolerant species such as willow and cottonwood at low flows. Vegetative succession occurs, resulting in development of a climax community. Channel migration then causes the cycle to repeat.

242. At any time, the floodplain of an unaltered river contains several successional stages and exhibits a high level of habitat diversity. Streambank protection projects are intended to impose stability and reduce the rates of change in this dynamic fluvial system. Longterm impacts result from the physical stability imposed on the fluvial system. Rates of lateral migration are reduced, and new backwater habitats are not formed to replace those gradually lost to sediment deposition.

243. The environmental benefits that can be attained from a project depend on the existing habitat and aesthetic conditions, the erosion pattern or conditions, and the streambank protection methods

suitable for the erosion and environmental conditions. The environmental features improve environmental quality through one or more of the following: establishment of riparian vegetation, creation of habitat diversity for fish, creation of suitable substrate for benthic organisms, and preservation or enhancement of visual quality. Desirable design, construction, and maintenance procedures may be unsuitable for a specific stream, stream reach, or project site. It is incumbent on the designer or planner to identify the opportunities for improvement of habitat and aesthetic conditions for each project.

244. Terrestrial habitat quality is affected by loss of riparian vegetation through clearing and bank preparation. Land use changes, such as intensification of agriculture, often occur after the protection structure is completed, further reducing the available riparian habitat. Wildlife habitat is enhanced by designs that use vegetation as a design component or which result in sedimentation and establishment of vegetation; construction practices that minimize clearing for access and utilize water-based and in-channel construction; and maintenance procedures that preserve vegetation while protecting structural integrity and allowing for inspection. Preservation of riparian vegetation enhances the edge effect and serves to maintain the linear nature of the riparian zone. Environmental features that enhance riparian vegetation include such things as composite revetment, bank sloping, excavated bench design, water-based construction, and maintenance categories for revetments.

245. Bank and channel stabilization projects result in more uniform depth and velocity conditions, decreasing habitat diversity for fish. Designs that cause variations in channel depth and velocities increase fish habitat diversity. Zones of deep water and reduced velocity develop around structures which extend into the stream. Scour holes form at the riverward end of hard points, jetties, and dikes. The creation of deep-water habitat is especially important in uniformly shallow channels. The area between intermittent structures or between an earth core dike and the bank is a slack-water zone. These low-velocity areas provide shelter from currents and are used as spawning and nursery areas. Boulders placed on revetments provide hiding cover and create eddies.

Flow over stone on jetties, hard points, and revetments produces riffle-like habitat for fish.

246. Benthic organisms, important as fish food and as processors of organic material, require either a stone or rocky substrate or a stabilized sediment substrate. Sediment adjacent to streambank protection structures becomes stabilized, and deposition areas develop in low-velocity areas such as Kellner jack fields, behind fence retards, on the land side of earth core dikes, and between intermittent structures, such as hard points and jetties. In channels where stable, rocky substrate is scarce, stone, rock, or concrete bank protection structures provide suitable benthic substrate not previously available. The idea that stone structures are beneficial to the benthic community should be tempered with the recognition that some streams may already be "saturated" with stone structures. Additional use of stone structures along these streams will therefore tend to reduce overall habitat diversity.

247. Aesthetic impacts of bank stabilization projects are determined by the extent to which the project is visually compatible with the existing riparian and channel environment. Visual impacts are reduced by use of vegetation in the design or natural regrowth of vegetation and the use of natural-appearing river gravel and cobble. Vegetation softens the rigid, unnatural lines of bank protection measures and helps blend the construction area with the existing vegetation and adjacent land use. Natural regrowth is sometimes preferred to planting because native species common to the area will result. Maintenance of vegetation is required, especially in the first few growing seasons, to ensure that it attains adequate size and density to prevent erosion. After establishment, vegetation is maintained to ensure that the vegetation type, density, or size does not endanger the integrity of the bank protection structure. Use of stone that appears natural to the river environment may be limited by local availability.

Recommendations

248. The incorporation of environmental features in streambank

protection requires consideration of habitat and aesthetic values in design, planning, construction, and maintenance. For a project to result in positive environmental contributions and minimize adverse environmental impacts, habitat and aesthetic factors cannot be added on at the end but rather must be integrated with hydrologic, hydraulic, and geotechnical data during all phases. If consideration of environmental factors is delayed until after the formulation of alternatives, opportunities for incorporation of environmental enhancement features may be lost. This report is a catalog of environmental features that should be used for formulating alternatives in design, planning, construction, and operation phases. These features can be used as a starting point in development of environmentally sound procedures. Further information pertaining to the features is available in the references and from appropriate organizations.

249. Further research should be pursued in several areas related to streambank protection. The use of vegetation for streambank protection is beneficial because of its contributions to wildlife habitat and aesthetics. Further research should be conducted to identify plant species and propagation methods suitable for a wider range of erosion conditions. The impact of articulated concrete mattress revetments on fish and benthic habitats should be further investigated to fully quantify habitat changes.

250. Numerous innovative designs have been used for streambank protection as part of the Section 32 Program and in other activities of the Corps and other agencies. Many of these designs appear to be successful from an engineering standpoint, but the environmental effects of these designs are not monitored beyond the initial operations inspections. The long-term effects on habitat and aesthetics should be documented.

251. Bank and channel stabilization projects result in basinwide changes in floodplain habitats. Land use changes in the basin further reduce available terrestrial habitats. The basinwide (or long reach) implications of bank stabilization for land use and habitat diversity changes should be documented when evaluating the impacts of projects.

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APPENDIX A: BACKGROUND INFORMATION

Introduction

1. The feasibility and effectiveness of a given environmental feature are strongly influenced by the physical and institutional setting. Many of the features described in this report have been applied only in certain limited geographic areas. Streambank protection designers considering use of a scheme, feature, or method previously untested in their region should familiarize themselves with the conditions for which the environmental feature was originally developed. Accordingly, background information on the Willamette, Missouri, Sacramento, and lower Mississippi Rivers and the Yazoo River basin is provided in this appendix.

Willamette River

Basin characteristics

2. The Willamette River basin is located in the northwest quadrant of the State of Oregon (Figure A1). The dimensions of the basin are approximately 75 by 150 miles, with the valley floor being nearly 30 miles in width. Although the Willamette drains approximately 12,000 square miles, the Willamette Valley floor is made up of only 3,500 square miles. The remainder of the area consists of mountain slopes on three sides and a belt of foothills paralleling the Cascade Range. The 3,500-square-mile valley floor is a broad, flat floodplain with intermittent gently rolling hills (Gleeson 1972).

3. The river flows generally northward from tributaries of the Coast and Cascade Ranges and has a total length of 187 river miles from its source to its confluence with the Columbia River (Honey 1975). The Willamette and its main tributaries have broad floodplains and meander belts. These floodplains are somewhat less extensive in the northern reaches, where the river is more confined by topography (Klingeman 1973).

4. The soils of the Willamette basin consist of a layer of

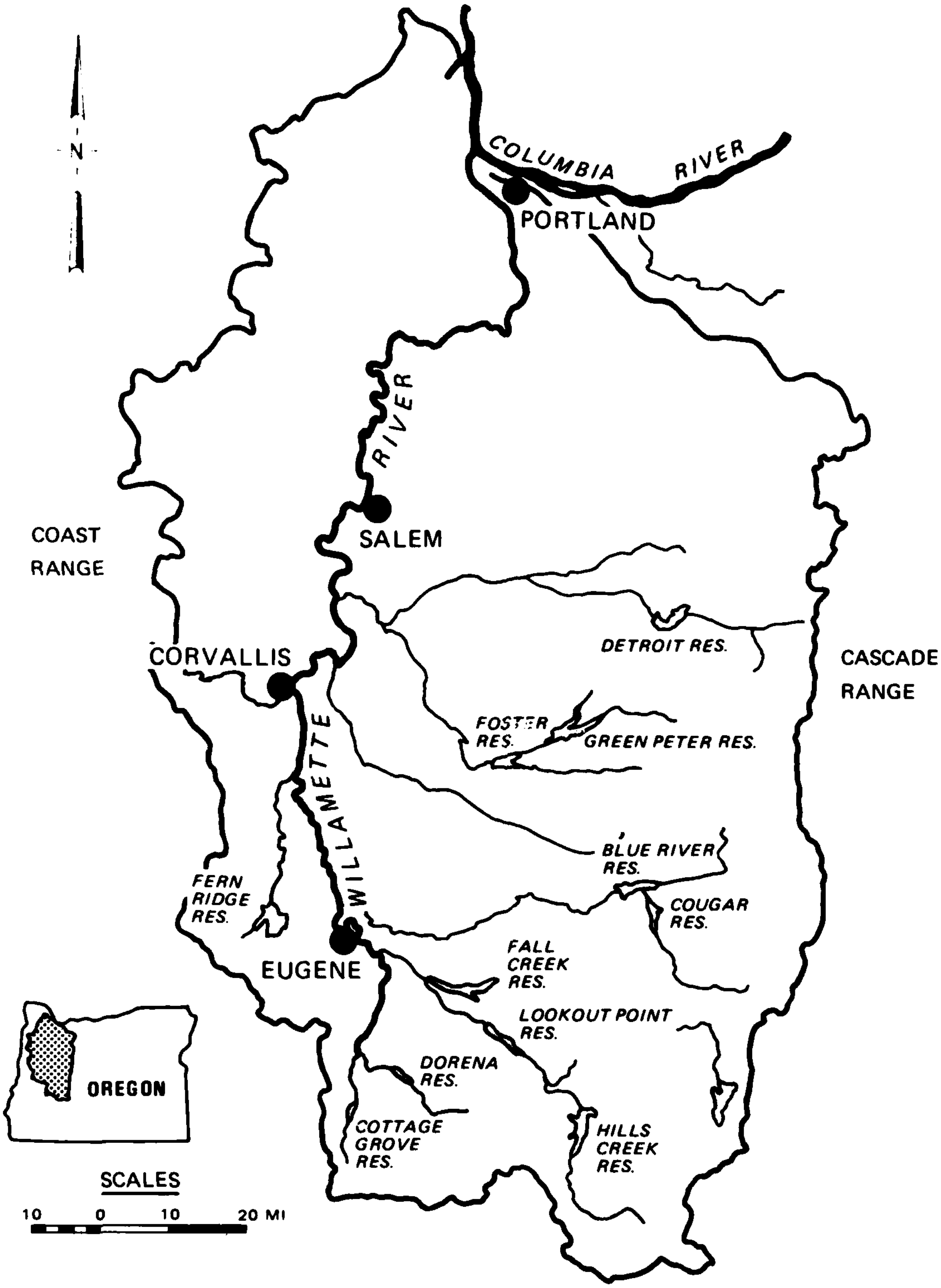

Figure A1. Willamette River basin, Oregon

floodplain soils covering older strata. These floodplain soils are sandy loams, silt loams, or silty clay loams. These soils drain rapidly during floodwater recessions and are sufficiently uncompacted and non-cohesive that erosion and bank caving occur readily as a result of soil particle washout (Klingeman and Bradley 1976). Streambanks are composed of sand and silt layers 20 ft or more thick over gravel layers that are 10 ft or more above the summer water levels (Klingeman 1981).

5. There is great variability in velocity in the Willamette River and principal tributaries, both with respect to time and location in the channel cross section. During large floods, local velocities may reach 18 ft/sec. Flows of 10 ft/sec for large flows within the banks are common (Klingeman and Bradley 1976). Suspended sediment concentrations average about 60 mg/ℓ and channel slope ranges from 2.0-5.0 ft/mile (American Society of Civil Engineers (ASCE) 1965). Mean annual discharge is 31,050 cfs at Wilsonville (Todd 1970). Summer discharges are small, and sluggish flows occur in many reaches of the river. The greatest bank erosion occurs during winter high-water periods (Klingeman and Bradley 1976).

6. Major engineering works in the Willamette basin include a system of storage reservoirs in the headwaters and along major tributaries and streambank protection revetments (US Army Engineer District (USAED), Portland 1975). Dredging was common prior to the 1970's, but a decline in commercial navigation above Portland has led to the cessation of dredging. Limited gravel mining is allowed above the waterline (bar scalping) and behind previously constructed berms (Klingeman 1979).

Streambank erosion

7. Streambank erosion along the Willamette is due to the meandering behavior of the river. There are indications that the channel has a historic meander width of 5 miles between Corvallis and Eugene (Klingeman 1979). Farther downstream the river becomes entrenched in the valley floor and lateral movement is restricted. According to Klingeman and Bradley (1976), factors contributing to the extensive meandering of the Williamette River include:

a. General flatness of the valley floor and lack of constraining topography.

b. Variability of magnitude in stream discharge.

c. Ease of transport of the valley sediments, especially during periods of large discharge.

d. Variable resistance of the streambank to erosion, although all banks are susceptible to erosion under vigorous attack of river currents.

e. Disturbances to streamflow such as gravel bars which set up transverse currents.

8. Typically, erosion extends along banks for distances of a few hundred feet to 3000 ft or more and progresses into the bank at rates of 10 ft or more per year (Klingeman 1981).

Ecological resources

9. Aquatic habitat. Viable anadromous fish runs have been restored in the Willamette. The fish runs had declined due to pollution in the river but have increased in recent years, partially due to water pollution abatement efforts begun in the 1960's (Gleeson 1972). The revitalization of the anadromous fish runs is of high public concern due to the economic and recreation potential. Willamette river gravel is important because it provides spawning media for the anadromous salmonids (Klingeman 1979). Accordingly, the agencies involved with fishery resources are interested in all actions that might change the transport of gravel in the river.

10. A sediment transport investigation was conducted (Klingeman 1981) to identify gravel recruitment processes and characterize a gravel budget (inputs, outputs, and storage) for the Willamette main stem and tributaries. The gravel budget for a given reach is quite variable and is strongly influenced by streambank erosion. Bank erosion is the major source of gravel where the streambed remains stable. For years without significant high-flow events, bank erosion is an important contributor to the instream gravel supply. When bank erosion in a reach is prevented, there is greater erosion of inchannel bars, if river discharges are high enough to cause bed-load transport. It was determined that the Willamette tributaries do not contribute gravel to the main stem under

normal flow conditions. The relatively large discharges required to transport sediment occur infrequently due to flood control regulation (Klingeman 1981).

11. Terrestrial habitat. Land use within the Willamette Valley is primarily agricultural. Of the 2.2 million acres, approximately 500,000 acres are in urban uses, 700,000 acres are in woodland, and the remainder is farmland. Intensive farming occurs on most of this land. Major crops include snap beans, sweet corn, strawberries, and other row crops. Rye grass and other seed crops are grown in the valley. Pasture and land devoted to growth of silage, corn, hay, and other crops related to livestock production account for about one-fourth of the cropland (USAED, Portland 1975).

12. A recent study documented the changes in riparian land use along a 60-mile reach of the river. Aerial photography was used to determine land use and vegetation changes for the period 1972-1981. The mapped categories included water, agriculture, development, and aggregated vegetation. The development category included sand and gravel operations along with industrial and urban development. The aggregated vegetation category included all woody, herbaceous, and grassy vegetation. The results of the comparison indicated progressive loss of riparian habitat to agricultural and development uses. Total acreage of riparian vegetation was reduced by 13 percent (726 acres), with 10 percent converted to agriculture (567 acres) and 3 percent (159 acres) to development (Frenkel, Heinitz, and Wickramaratne 1983).

Institutional factors

13. The Corps of Engineers (CE) began constructing revetment in the Willamette basin in the 1930's. Construction proceeded rapidly and has declined in recent years with completion of most authorized bank protection work. The work has been done under authority of the Flood Control Acts of 1936, 1938, and 1950. The revetments have been constructed as components of reservoir projects to prevent erosion caused by prolonged bank-full flows and as part of the Willamette River Basin Protection Project (USAED, Portland 1975).

14. Construction of bank protection by the CE requires local

participation. The degree and type of participation for a particular project is determined by the authorizing Flood Control Act. Local sponsors, such as water control districts, state agencies, or cities, must agree to provide rights-of-way for access, and in some cases maintain the revetments. The revetments constructed prior to 1953 are maintained by the Corps. Revetments constructed after 1953 (under authority of the Flood Control Act of 1950), about half the total number, are maintained by local sponsors at their own expense (USAED, Portland 1975, Forbes et al. 1976).

15. Greenway program. The Willamette River Greenway Program was initiated by the Oregon Legislature to provide comprehensive land use planning for the waterway. The goal is to allow coordinated uses of the river while limiting the intensity of uses. The greenway corridor includes the lower 70 percent of the river main stem and extends from the channel to an elevation of 150 ft above ordinary low water level, up to a maximum of 320 acres per river mile. Use of lands along the greenway is controlled by zoning established by local planning authorities and standards set by a State commission. These standards include such things as preservation of agricultural land, public access, protection of fish and wildlife habitat, and provision of recreation needs (Frenkel, Heinitz, and Wickramaratne 1983).

16. Coordination committee. The Willamette River Coordination Committee (WRCC) was formed in 1977 to advise the Portland District in the protection of streambanks along the Willamette. The WRCC consists of representatives from Federal and State fish and wildlife, conservation, and natural resources agencies. The purpose of the committee is to establish engineering and environmental criteria for Willamette River bank protection work* (see Part V of Main Report, section Advisory Group).

Streambank protection

17. Streambank protection along the Willamette and its tributaries is primarily quarry-run stone revetment (Figure A2) (USAED, Portland

* Personal Communication, 1983, Mr. Thomas Morse, USAED, Portland.

Figure A2. Stone revetment along the Willamette

1975). The revetment rapidly vegetates after placement. The revetments are most often placed on the concave banks of bends in the channel where the river current is directed into the bank. The underwater portion of the revetment is prepared by constructing a toe trench excavated into the river bottom. Above the toe, the bank is sloped to a 1V:2H slope. About 120 miles of riverbank are protected by stone revetment.

18. Until about 1980, common revetment maintenance included annual vegetative clearing to increase visibility for inspections and prevent damage to the revetment by the vegetation. Clearing involved removal of all plant material down to the sod layer from the water surface to the top of the bank. Clearing has recently been restricted to material greater than 6 ft in height or 2 in. in diameter (Bierly and Associates 1980). Maintenance of revetments also includes filling holes in the riprap blanket. A yearly inspection by helicopter in May determines which revetments have been damaged during the high flows of the spring and winter. Clearing and repair of damage then usually begins in July (USAED, Portland 1975).

Environmental features

19. The major environmental feature on the Willamette is a system of revetment classification for maintenance purposes. Four categories of revetments have been delineated (see Part V, section Revetment Maintenance Categories). The categories are based on (a) area protected (potential economic loss, loss of life) and (b) likelihood of failure (i.e., the erosional setting). For each category, vegetative restrictions and revetment encroachment standards have been developed. The vegetative restrictions determine the size, kinds, and density of vegetation permitted on the revetment. Revetment encroachment standards limit the types of structures that may be built near the revetment. If, on annual inspection, conditions have changed at the revetment, the category classification is altered accordingly.

Recent findings

20. Hjort et al. (1983) compared fish and benthic macroinvertebrates from natural and nearby revetted banks on the Willamette to determine the impact of revetments on species abundance and distribution. The diverse aquatic habitats along the natural bank promote greater species diversity (number of different species), but densities of organisms are greater along the revetments. The fish along the revetment were smaller in size than the same species found along natural banks. This was attributed to the moderate water current and presence of interstitial spaces. Small fish generally prefer lower water currents than larger fish of the same species, and small fish are more successful at foraging for food within the interstitial spaces. Similar benthic species were found at natural banks and revetted habitats. The greater benthic densities at the revetments are attributed to greater diversity of macrohabitats, larger surface area for colonization, and greater stability of the stone as compared to sediments (Hjort et al. 1983).

Missouri River

Basin characteristics

21. The Missouri River flows from its headwaters in Montana,

Wyoming, and Colorado to its confluence with the Mississippi just upstream from St. Louis. The Missouri River and its tributaries drain approximately 500,000 square miles, one sixth of the contiguous area of the United States (Figure A3). River length from headwater to Mississippi confluence is approximately 2500 miles.

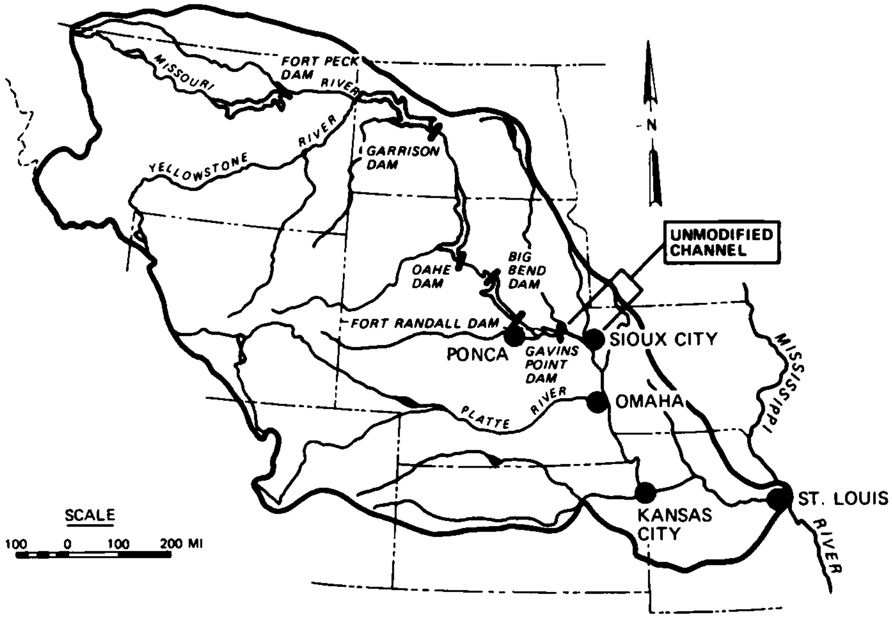

Figure A3. Missouri River Basin

22. The basin is approximately 1300 miles long and 700 miles wide. Basin topography is highly variable: canyons and rugged mountain terrain in the upper part of the basin, regions of smoothly sloping terrace lands and the hill plains of the central lowlands, and finally the rugged upper Ozark Plateau in the lower reaches (Burke 1976). Along the middle Missouri, average annual discharge is approximately 54,000 cfs and total dissolved solids range from 300-600 mg/ℓ (Slizeski, Andersen, and Dorough 1982). Channel slope averages 0.9 ft/mile between Sioux City, Iowa, and the mouth (ASCE 1965). Channel bed material varies from coarse to fine-grained sediments (OCE 1981, Appendix E). Channel velocities average 4-6 ft/sec (Burke and Robinson 1979).

23. Major engineering works on the Missouri River consist of six

large storage reservoirs on the main stem of the upper river, numerous dikes and revetments on the lower river, and levees that parallel the lower river. Sioux City, Iowa, is the head of commercial navigation. The river between Gavins Point Dam and Sioux City is basically unmodified. The river below Sioux City has been converted from a wide, braided stream into a single channel with gently sinuous bends using dikes, revetments, and cutoffs. Water surface area has been decreased 50-67 percent (Funk and Robinson 1974, Morris et al. 1968). Since much of the upper river is impounded, little bank erosion occurs; however, there are some relatively unaltered short reaches downstream of the dams that experience serious degradation and bank erosion. Some streambank protection work has been done in these reaches (Burress, Krieger, and Pennington 1982).

Streambank erosion

24. The unmodified river experiences frequent channel relocation by gradual bend migration or more rapid cutoffs during flood events, and is characterized by braided channels, islands, shifting sandbars, eroding banks, and a rapid current with respect to its size. The unmodified river channel is in a constant state of change, which produces a diversity of habitat not available in the other reaches (Kallemeyn and Novotny 1977).

25. Streambank erosion on the modified reach of the Missouri has been somewhat abated by the construction and operation of the upstream dams. Prior to dam construction, extensive erosion took place due to conditions resulting from channel migration (braided channels, development of sloughs and backwater areas) and variations in streamflows (unregulated flood discharges) (Burke 1976). The impact of dams on streambank erosion is evident when predam and postdam erosion rates are compared. For example, for the reach between Gavins Point Dam and Ponca, Nebraska (Figure A3), the average erosion rate was 202 acres per year prior to operation of the dam. The average erosion rate after dam construction is 177 acres per year (OCE 1981, Appendix E). Although the average annual erosion losses have decreased significantly since the closure of the dams, streambank erosion still remains a serious problem

due to the development of the floodplains.

26. On the reaches of the Missouri River downstream from Garrison Dam in North Dakota and Fort Randall Dam in South Dakota (Figure A3), the major causes of streambank erosion, in order of estimated importance, are channel meandering, varied streamflow, channel alignment structures (e.g., dikes), and wave attack. These reaches also experience significant river stage fluctuations due to normal daily power-generation fluctuations. Streambank erosion downstream from Gavins Point Dam is due to divided flow conditions, channel meandering, sediment transport, and winter ice jams (OCE 1981, Appendix E). This reach has essentially long-duration steady-state discharges, without the fluctuation experienced in the other two reaches. Other factors contributing to erosion along the Missouri River are saturated banks, bank line undercutting (erosion at the base of slope), high sand content, and frequent freeze-thaw cycles during the winter (OCE 1981, Appendix E).

Ecological resources

27. Much of the upper Missouri River has been converted into lentic (still-water, nonflowing) habitats by construction of six large dams. This discussion centers around the unimpounded reaches downstream of the dams and the unimpounded lower river.

28. Aquatic habitat. Modification or "channelization" of the Missouri river has had drastic impacts on the amount and nature of aquatic habitat. Total water surface area, backwater marshes, islands, chutes, sloughs, snags, and brushpiles have all been greatly reduced. Commercial fish harvest declined 80 percent between 1947 and 1963 (Burke and Robinson 1979), and sportfish catch rates and harvest are presently greater in unmodified upper reaches than lower reaches (Groen and Schmulbach 1978). Nevertheless, the modified river still supports more than 50 species of fish (Hesse et al. 1982; USAED, Omaha 1982), most in densities that compare favorably with the "unchannelized" upper reaches (Hesse et al. 1982).

29. Pool-type habitats associated with dikes and revetments, at least to a certain extent, replace some of the lost low-velocity backwater habitats and are extremely important to most fish species

(Kallemeyn and Novotony 1977; USAED, Omaha 1982; Munger et al. 1974). Marshes along the 52-mile unchannelized reach between Gavins Point Dam and Sioux City are extremely important habitats for many species of larval fish; however, these marshes are threatened by lower water levels caused by main channel bed degradation and upstream diversions (Kallemeyn and Novotony 1977, Hesse et al. 1982). The main stem reservoirs export large amounts of plankton to the lower reaches (Hesse et al. 1982). Riprap used to construct the river-training structures is densely colonized by attachment-type benthic organisms (Burress, Krieger, and Pennington 1981; Munger et al. 1974; Hesse et al. 1982; Kallemeyn and Novotony 1977). Density of burrowing-type benthic organisms is low in both upper and lower reaches due to shifting substrates (Morris et al. 1968).

30. Terrestrial habitat. Natural habitat along much of the Missouri River is limited to intermittent areas of mature timber located in a narrow band immediately adjacent to the river, a few timbered islands, and government-controlled preserves (US Fish and Wildlife Service 1980). Habitat quantity and quality have fallen sharply in recent years (Funk and Robinson 1974). Clapp (1977) mapped habitats within 0.6 mile of two reaches of the upper river with a total length of 120 miles between Fort Randall Dam and Sioux City. His findings were as follows:

Habitat type	Percent
Agricultural and urban development	60
Cottonwood-dogwood	16
Cottonwood-willow	9
Elm-oak	7
Cattail marsh	3
Sand dune	3
Sandbar	1

Habitats were rated subjectively according to their value to each of nine faunal groups and interspersion. Cattail marsh received the highest total rating and sand dune the lowest.

31. Peterson and Segelquist (undated) noted incidental sightings

of raccoon, beaver, white-tailed deer, muskrat, cottontail rabbit, false map turtle, spiny softshell turtle, smooth softshell turtle, snapping turtle, eastern gray squirrel, and coyote in conjunction with fish sampling activities on the lower river in 1977 and 1978. This study identified and evaluated six habitat types: swift water, slack water, sandbar, cattail marsh, bottomland forest, and agricultural land.

32. Munger et al. (1974) reported the following distribution of habitat types for the floodplain along the lower river from Rulo, Nebraska, to the mouth:

Habitat type	Percent
Agriculture	82
Young forest	11
Mature forest	6
Willows	1

Mature hardwood forests are the most biologically productive and diverse habitat. Willow stands are important because they are the successional precursor for the forest.

Institutional factors

33. CE role. Streambank protection projects have been authorized in the upper impounded Missouri River and in conjunction with channel modifications on the lower Missouri for navigation purposes. Projects in the upper Missouri were authorized under the Flood Control Acts of 1944, 1946, 1948, 1963, and 1968, and amendments, and the Section 32 Program authorization (Water Resources Development Act of 1974). The Missouri River Bank Stabilization and Navigation Project, which provides protection on the lower Missouri from Sioux City to the mouth of the river, was authorized by the Rivers and Harbors Act of 1945. Maintenance of streambank protection projects is performed either by the CE or by local sponsor.*

34. Wild and Scenic Rivers Act. The Missouri River from Gavins

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* Personal Communication, 1983, Mr. Doug Plack, USAED, Omaha.

Point Dam to Ponca, Nebraska, has been designated as a National Recreational River under the Wild and Scenic Rivers Act. This authority includes new bank stabilization in addition to maintenance of all existing streambank control structures along the river reach. When the Recreational River Project is funded, the CE will assume responsibility for operation and maintenance along the Gavins Point Dam to Ponca, Nebraska, reach after obtaining the required land interests.*

Streambank protection

35. The most common methods for streambank protection on the Missouri are transverse dikes and revetments made from quarry-run limestone. Many of the revetments are not placed against the protected bank, but instead resemble dike structures that parallel the current a short distance from the bank. A small amount of new construction is performed each year to improve trouble spots and refine the existing project. Existing structures are often damaged by wave and current action, freeze-thaw action, and ice floes. Repairs generally consist of adding more stone for reinforcement and reconstruction.

Environmental features

36. Environmental features that increase habitat diversity and preserve riparian vegetation have been incorporated in streambank protection structures. Hard points, short dikelike structures for shallow reaches, create small areas of slack water and scour holes. Hard point crowns support natural vegetation. Composite, reinforced, and windrow revetment designs result in preservation of upper bank riparian vegetation valuable as wildlife vegetation. Earth core dikes provide slackwater habitat between the structure and the streambank.

Recent findings

37. Burress, Krieger, and Pennington (1982) reported results of fish and benthic macroinvertebrate sampling in the vicinity of natural banks and several types of bank protection structures along a reach of the upper river downstream from Garrison Dam. Bank protection structures supported higher densities of benthic organisms than natural banks

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* Personal Communication, 1983, Mr. Doug Plack, USAED, Omaha.

due to the large numbers of attachment-type organisms on rock surfaces. Fish catch rates were not significantly different at different types of structures, although dike fields supported the most diverse fish community. Environmental aspects of Missouri River dike construction and maintenance are summarized by Burch et al. (1984).

Yazoo River Basin

Basin characteristics

38. The Yazoo River basin is located in the northwestern quadrant of Mississippi (Figure A4). The Yazoo basin has a length of 200 miles and a maximum width of 100 miles, and may be divided into two distinct physiographic regions, the Yazoo uplands and the Yazoo alluvium, or Mississippi Delta. The uplands portion of the basin is the primary area of interest to this report, since the environmental features reviewed were confined to that part of the basin. The Yazoo uplands area comprises 4.2 million acres of gentle to steeply rolling uplands or hills with scattered flatlands and valleys. In contrast, the Mississippi Delta area is flat, and comprises about 4.3 million acres (Lower Mississippi Region Comprehensive Study (LMR) 1974).

39. The Yazoo drainage basin encompasses 7450 square miles (Todd 1970) comprised of a complex network of subbasins. Creeks and smaller streams rise in the upland areas to form the principal streams. The Tallahatchie and Yalobusha Rivers join near Greenwood, Mississippi, to form the Yazoo River. The Yazoo then flows southwesterly for 169 miles through the delta to join with the Mississippi near Vicksburg (Keown, Dardeau, and Causey 1981). Average annual discharge is 9619 cfs at Greenwood (Todd 1970).

Streambank erosion

40. Streambank erosion along the Yazoo basin hill tributaries is extensive and locally severe. Whitten and Patrick (1981) document abrupt changes in channel position, sinuousity, 200-300 percent increases in channel width, and tens of feet of deepening, all within the last 40 years. Losses of agricultural lands and repair or replacement

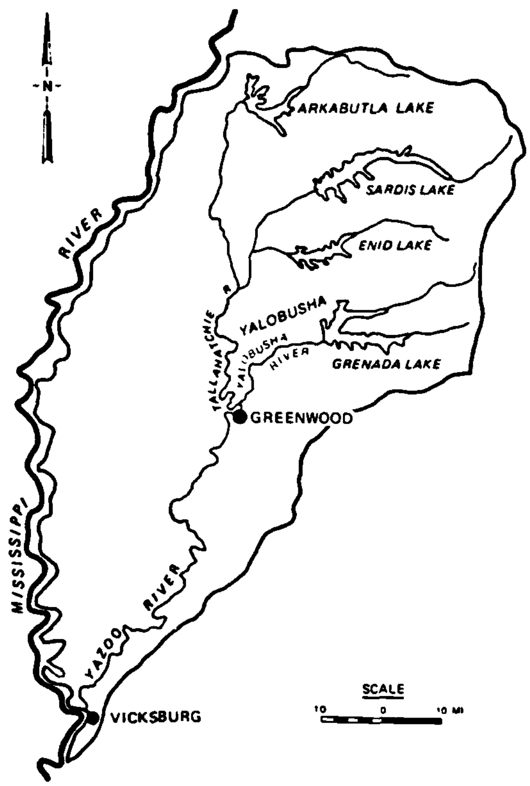

Figure A4. Yazoo River basin, Mississippi

of culverts and bridges have been quite costly. The major cause of this erosion appears to be bed degradation due to channel modification, cutoffs, loss of geologic control (e.g., removal of a resistant strata overlying an erosive strata), flood control activities, and changes in base level. Reservoir construction and operation and agriculture are also factors (OCE 1981, Appendix F; Whitten and Patrick 1981). Secondary causes include natural meandering, bank failures caused by hydrostatic pressure, overbank drainage, and extreme storm events (OCE 1981, Appendix F).

41. Bed degradation is indicated by the presence of numerous knickpoints or headcuts, some several feet high. Since bed degradation is such an important cause of erosion in the Yazoo basin, bank protection methods that control degradation, e.g., grade control structures, or protect the streambank toe are often effective. Streambank protection along these streams is often a matter of bed stabilization (OCE 1981, Appendix F).

Ecological resources

42. Aquatic habitat. The Yazoo basin has an abundance of aquatic resources. There are approximately 11,400 miles of streams in the uplands. Many of these upland streams have been enlarged and aligned, which has severely reduced fish habitat quality. The loss of aquatic habitat is most severe in the upland hill areas because there are few naturally occurring lakes (LMR 1974).

43. The delta part of the Yazoo basin has numerous natural lakes.

A system of delta oxbow lakes and associated timber brakes or backwater areas provide valuable fishery habitat. Tracts of wetlands such as undisturbed marshes, swamps, and overflow bottomland forests are an important resource in the delta. These areas provide nursery and breeding areas for numerous aquatic as well as wildlife species (LMR 1974). However, more and more of these areas are being drained and destroyed for agriculture.

44. Terrestrial habitat. Wildlife habitat is greatly affected by changes in land use. To date, over 80 percent of the Yazoo basin has been cleared of forests. This change in land use has reduced considerably the available wildlife habitat (USAED, Vicksburg 1972). The predominant land use in the Yazoo basin is agriculture. In the upland hill area, forestry and forest product industries are prominent in addition to agriculture. In the delta area, intensive agriculture has been made possible by clearing of forests and flood protection measures. The Yazoo basin delta area is the most productive agricultural area in the state. Major crops include soybeans, cotton, small grains, corn, pasture, and livestock (USAED, Vicksburg 1972).

45. The forest industries and intensive agriculture in the Yazoo basin were made possible by extensive clearing. The initial development of the uplands for agriculture resulted in extreme soil erosion. A program of reforestation has provided wildlife habitat as well as soil stabilization (LMR 1974).

Institutional factors

46. Development of the Yazoo basin for agriculture and forestry purposes has been influenced heavily by actions of the Federal Government. In the upland hill area, the early agricultural practices and lack of conservation resulted in extensive soil erosion. The early economy of the hills was centered around corn and cotton production. As the flatter lands became crowded, farming began on the hillsides, exposing the loosely compacted sandy loam to erosive forces. Uncontrollable erosion followed, resulting in extensive damage to stream channels in the hills due to excessive sediment loads and loss of farm productivity.

47. In 1944, Congress provided for Federal participation in

planting trees, grasses, and legumes on unprotected hillsides. This vegetative cover assists in retaining the soil and reducing the magnitude and intensity of storm runoff. Nearly 680 million loblolly pine trees were planted in addition to 312,000 acres of grasses and legumes. Due to these actions a greater degree of stability has been restored to the hills (LMR 1974).

48. Development in the delta area has been made possible by prolonged land reclamation efforts. Farming in the delta required clearing land and building earthen levees to protect against the annual floods. Under the Federal Swamp Lands Acts of 1849 and 1850, wetlands and low-lying areas were drained and numerous levees were constructed (LMR 1974).

49. As a result of the 1927 Mississippi River flood, the Flood Control Act of 1928 was enacted, which provided for flood control work along reaches of the Mississippi River and its tributaries. In the Yazoo basin, the Act and subsequent amendments resulted in construction and improvement of existing levees, bendway cutoffs, channel alignment, and enlargement. A total of 459 miles of channel modification, e.g., bendway cutoffs, channel enlargement, and stabilization, and 159 miles of levees have been authorized. Four multipurpose reservoirs built on the Yazoo tributaries provide flood protection for the basin (Figure A4) (LMR 1974). Streambank protection in the Yazoo basin has been accomplished under the Section 32 Program authorization, the Flood Control Act of 1946, as amended, and yearly authorizations under the Mississippi River and Tributaries Act, as amended.*

Streambank protection

50. The lower velocities and discharges encountered in the Yazoo River basin allow use of streambank protection measures that would be ineffective on larger streams. The relation between bed degradation and streambank erosion in the hills often requires that these two processes be addressed together. Failure to stabilize the streambed has often led to failure of streambank protection structures due to undercutting of the streambank toe. Conversely, grade control structures and toe protection

* Personal Communication, 1983, Mr. James Hines, USAED, Vicksburg.

are often used effectively on Yazoo basin streams. Typical streambank protection methods used in the Yazoo basin include stone riprap revetment, tranverse stone dikes, wire and fence retards, and jack fields.

Environmental features

51. Several of the designs tested at Section 32 Program demonstration sites on Yazoo basin streams included the use of vegetation to stabilize and protect upper banks. Both planted and naturally occurring vegetation were used. In some cases, stone toe protection has been placed using equipment on one side of the channel or operating within the channel to avoid destroying riparian vegetation for access. Grade control structures are sometimes preferred from an environmental standpoint, since construction and maintenance do not require extensive clearing and disturbance along long segments of bank line. Bed stabilization with these structures facilitates natural revegetation of formerly eroding bank lines.

Recent findings

52. The Section 32 Program Main Report and Appendix F (OCE 1981) contain extensive information on the performance of several demonstration projects constructed at 11 general locations along several Yazoo basin tributaries. All locations were in the uplands portion of the basin. Bank protection methods tested include bank sloping, channel relocation, excavated bench design, toe protection, fence retards, and grade control structures. No biological field studies of the effects of these structures on fish and wildlife have been conducted.

Sacramento River

Basin characteristics

53. The Sacramento River basin is located in northern California (Figure A5). The Sacramento basin is about 280 miles long and up to 150 miles wide. The Sacramento River is approximately 200 miles long, running from tributary creeks in the upper basin to Collinsville, where it joins the San Joaquin River (USAED, Sacramento 1972). The river drainage area is approximately 26,300 square miles. The average annual

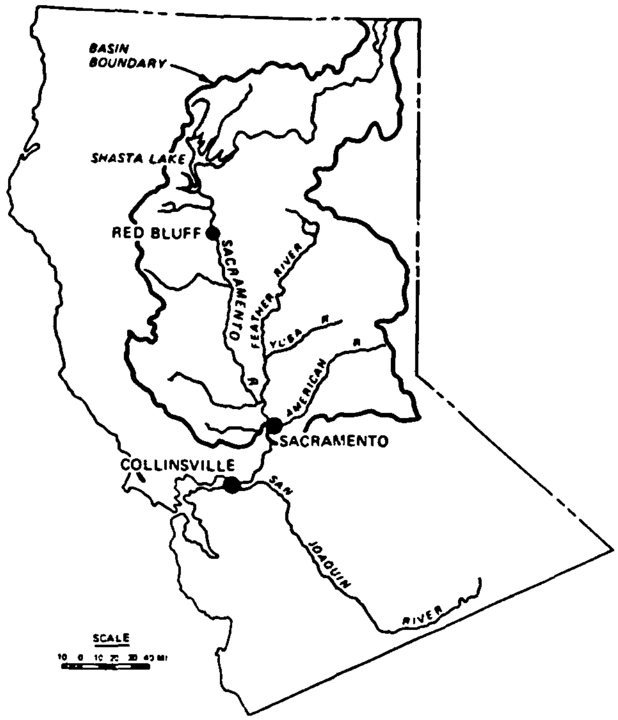

Figure A5. Sacramento River basin, California

discharge is about 25,000 cfs (USAED, Sacramento 1972). Suspended sediment concentrations are about 150 mg/ℓ and channel slope ranges from 0.4-2.0 ft/mile (ASCE 1965). Velocities observed at one Section 32 demonstration site (mile 176.5) ranged from 4-11 ft/sec (OCE 1981). ASCE (1965) noted that velocities during extreme floods range from 5-9 ft/sec and that the floodplain soils are primarily clays with some interbedded sand strata.

54. The Sacramento River is an alluvial stream with quite active meandering characteristics. Deposits from flood flows created upraised areas known as rimlands, which acted as natural levees. The rimlands confined the channel so that it is now incised and flanked on either side by broad rimlands and low-lying flood basins. Since flood basins proved to be prime agricultural land, levees were first constructed by early settlers in the latter half of the 1800's. Many of the early man-made levees were built atop the natural levees (Mifkovic and Petersen 1975).

Most of these early levees were built so close to the stream (40-200 ft) that streambank protection is now required to protect the existing levees built on top of them. Major engineering works along the Sacramento include extensive levees, streambank protection, and a system of storage reservoirs in the headwaters and along major tributaries.

Streambank erosion

55. The erosion rate along the Sacramento historically (1896-1974) is 15 ft of bank per year per stream foot, representing a loss of 1.82 acres per year for each stream mile (Brice 1977). Prior to the 1940's, high flood flows following spring snowmelt were the major cause of erosion. Presently, flows are regulated by storage reservoirs; however, this has resulted in heavy development along the river. Some streambank erosion is caused by wave wash from recreational boating made possible by sustained high summer flows from the dams (Mifkovic and Petersen 1975). Although regulation by the dams has decreased erosion by high flood flows, erosion still occurs at the sustained lower flows (USAED, Sacramento 1975a). Within the Sacramento Basin, about 250 acres a year are lost to bank sloughing (USAED, South Pacific 1977).

Ecological resources

56. Aquatic habitat. The Sacramento River supports a sizable sport and commercial fishery. Fishery resources include warmwater species such as black bass, crappie, white catfish, channel catfish, bluegill, and an anadromous fishery. The Sacramento River is the spawning area for all of the white sturgeon, 90-95 percent of the American shad, and about two-thirds of the adult striped bass in California (USAED, Sacramento 1972).

57. Terrestrial habitat. Outside the urban areas, the primary land use in the Sacramento Valley is agricultural. Diversions from the river are used to irrigate a large portion of the valley. Agricultural production includes truck crops, orchards, rice, safflower, milo, beans, sugar beets, alfalfa, and other grains (USAED, Sacramento 1975b). Since the early 1950's, there has been an increase in orchard production and a decrease in row, pasture, truck, and forage crop production. The shift from row crop production to orchard production decreases overall

wildlife habitat value. The row crop production provides greater habitat diversity and greater availability of life requisites, e.g., protective cover and food sources, for wildlife. The clean-tilled orchard lands thus have a lower value to wildlife than the row crop production (USAED, Sacramento 1972).

58. Berm areas inside the Sacramento River levees are ecologically important because they provide valuable riparian habitat. Because of the intensive agriculture in the valley, in some areas the berms support the only natural vegetation. Wildlife in semiarid zones, such as the Sacramento basin, are more dependent on riparian vegetation than in humid parts of the country (Mifkovic and Petersen 1975). Riparian vegetation along the Sacramento River includes cottonwoods, willows, oaks, and other woody vegetation. Numerous species of shrubs, forbs, and grasses grow with the trees to form a dense riparian habitat (USAED, Sacramento 1972). Because of its linear distribution and edge effect, the value of riparian vegetation as wildlife habitat far exceeds an equivalent acreage in a single block (USAED, Sacramento 1980). Habitat for a variety of wildlife and more than 140 species of birds is sustained by the riparian vegetation.

Institutional factors

59. Authority. In the early 20th century, comprehensive flood control plans for the Sacramento Valley were considered. A number of options were proposed including storage reservoirs, confining the rivers to single main channels, and improving the river channels to maximum capacity supplemented by leveed floodway bypasses (USAED, Sacramento 1972). The leveed floodway concept was adopted and became part of the Flood Control Act of 1917. The Act authorized the Sacramento Flood Control Project, a system of levees, overflow weirs, pumping plants, bypass channels, and channel enlargements. About 980 miles of levee was authorized for construction or improvement (USAED, Sacramento 1980). Subsequently, streambank erosion along the levee system prompted the implementation of the Sacramento River Bank Protection Project in 1960. This project provides for construction of bank erosion control works and for setbacks of levees. The project consists of two phases of construction.

The initial phase included 80 miles of bank protection and levee setbacks and was completed in 1974. A second phase of construction for 75 miles of bank protection and levee setbacks is to be completed in 1984. Authorization for the second phase included provisions to prevent environmental losses or to mitigate unavoidable losses concurrently with project construction (USAED, Sacramento 1980).

60. Costs. The Corps is responsible for construction of streambank protection structures and pays two-thirds of the project costs. The State of California is responsible for providing all lands, easements, rights-of-way, and utility changes and enough cash outlay to meet one-third of the total project costs. The non-Federal sponsor is the California Reclamation Board.

61. Maintenance. The Reclamation Board has responsibility for operation and maintenance of the levee system and constructed streambank protection structures. Responsibility for maintenance is transferred to local reclamation or levee districts. The local districts tax landowners within the district to finance the costs of maintenance (USAED, Sacramento 1980).

62. Wild and Scenic Rivers Act. Two reaches of the Sacramento River have been designated as wild, scenic, or recreational river areas under the Wild and Scenic Rivers Act (Public Law 90-542). The Sacramento River north of the city of Sacramento to Keswick Reservoir and the stretch from the river's source to Shasta Lake have been so designated. The act requires that in all planning for the use and development of the river and adjacent lands, Federal agencies are to give consideration to potential national wild, scenic, and recreational values (USAED, Sacramento 1972).

63. Recreation. Fishing, boating, water skiing, hiking, and camping are popular along the Sacramento River. There is heavy recreational use in spite of the limited access due to agricultural use and the levee system. A number of public and private recreation developments have been constructed along the leveed portion of the river (USAED, Sacramento 1972).

Streambank protection

64. Streambank protection along the Sacramento is primarily revetments constructed by placing quarrystone on a prepared slope. The normal construction method is to prepare a 1V:2H slope and place an 18-in. layer of quarry rock from 5 ft below the stream thalweg up to the low-water elevation. From the low-water elevation to the top of the bank, a 12-in. layer of quarrystone is placed (USAED, Sacramento 1975a).

65. Recently, a new bank protection method was designed for the middle Sacramento River. The design consists of short, vertical submerged vanes installed in concave bends. The vanes are aligned in series to counter the torque exerted by the flow in the bends and to reduce secondary currents responsible for undermining the bank (Odgaard and Kennedy 1983). This new design has not yet been utilized.

Environmental features

66. Modifications to revetment designs have been undertaken which result in preservation of upper bank vegetation and restoration or protection of the berm areas valuable as wildlife habitat. These modifications include reducing the design flow (see sections Modified Revetment Design and Berm Preservation, Protection, and Restoration, Part IV of main text).

Recent findings

67. The California Department of Fish and Game recently performed a study for the USAED, Sacramento, to determine the impacts of bank protection on fisheries, with primary emphasis on the chinook salmon (Schaeffter, Jones, and Karlton 1982). Impacts of streambank protection works on spawning, rearing of juveniles, and food sources of chinook salmon were evaluated. Fish and macroinvertebrates were sampled from riprap and natural banks between Red Bluff and Chico Landing between October 1980 and September 1981.

68. A total of nineteen species of fish were captured. At the riprapped banks, 33-68 percent of the catch were salmon fry and juveniles. Bluegill, goldfish, redear sunfish, and smallmouth bass were found only in riprap areas. At the natural banks, 54-85 percent of the fish were salmon. Salmon were from 0.84 to 4.57 times as abundant in

natural areas as riprap areas. Schaeffter, Jones, and Karlton (1982) hypothesized that the larger substrate in the riprap areas was responsible for the lower salmon numbers at the riprap sites. They suggested that the riprap crevices provided habitat for fish species not adapted to the swifter currents near natural banks and that these species compete with the salmon for food and may prey on salmon fry. However, no data were taken to establish whether or not such predation or competition actually occurs.

69. The captured fish were examined to determine components of the chinook salmon diet. The salmon diet is comprised principally (72 percent) of insects from the families Chironomidae (midges), Baetidae (mayflies), and Aphididas (aphids). There is no difference in consumption of the different families at the riprap or natural bank. Densities of the chironomids and aphids were similar at riprap and natural bank sites, but mayflies (baetids) were more numerous in the natural bank sections.

70. Chinook salmon fry were found to prefer sheltered areas adjacent to swift currents. The smaller fry prefer stream margins with bank cover such as fallen trees and undercut tree roots. In comparison of riprap and natural habitats, the fry showed a strong preference for the natural areas.

71. Salmon spawning areas were found to be clustered in crossings between river bends and in branching and braided sections of the river. No spawning occurred downstream of major tributary confluences, suggesting that little if any gravel enters the river from the tributaries. Schaeffter, Jones, and Karlton (1982) recommended (a) a portion of the meander belt between Red Bluff and Chico Landing be procured to ensure continued spawning and rearing habitats for salmonids, (b) further revetments be constructed of smaller substrate using bank slopes of 1V:6H or flatter in order to increase salmon spawning and rearing, and (c) alternatives for further streambank protection work should include spawning and rearing facilities that will support the impacted salmon runs.

Lower Mississippi River Basin

72. Although no environmental features are routinely employed in

lower Mississippi River streambank protection projects, an intensive biological field study of a 50-mile reach was conducted under the Environmental and Water Quality Operational Studies (EWQOS) of the Office, Chief of Engineers. Since results of this study contribute greatly to the state of knowledge of the effects of bank protection on large river ecosystems, the following background information is presented along with an overview of pertinent findings of the study.

Basin characteristics

73. The lower Mississippi River basin consists of the portion of the Mississippi main stem from the upper Mississippi-Ohio River confluence to the Gulf of Mexico (Figure A6). The basin, which covers portions of six states, is approximately 600 miles long; width varies from less than 50 miles to slightly over 150 miles (Keown, Dardeau, and Causey 1981). Due to the sinuous nature of the channel, river mileage is approximately 1,000 miles from Cairo, Illinois, to the Gulf of Mexico (ASCE 1965). The total drainage area (including tributary basins) for the lower Mississippi River is 102,400 square miles (LMR 1974). Suspended sediment concentrations at Vicksburg average roughly 1500 mg/ℓ (Keown, Dardeau, and Causey 1981). Channel slope above Baton Rouge is 0.4 ft/mile and is 0.01 ft/mile below Baton Rouge (ASCE 1965). Average discharge at Vicksburg is 576,500 cfs (US Geological Survey 1981). Average channel velocities typically range from 3-6 ft/sec (Pennington et al. 1980).

74. The floodplain and delta of the lower Mississippi River form the largest continuous area of alluvial soil in the United States. The floodplain consists primarily of sand and silt, progressively grading to very fine sand and silt in the lower part of the basin (Keown, Dardeau, and Causey 1981). Composition of the bed material varies from gravel and coarse sands to very fine silts

Streambank erosion

75. Streambank erosion along the lower Mississippi River is the result of channel migration, heavy sediment load, large variability in discharge, high discharge rates, and bank instability. Sloughing of saturated banks, flow slides, liquefaction, and similar phenomena are

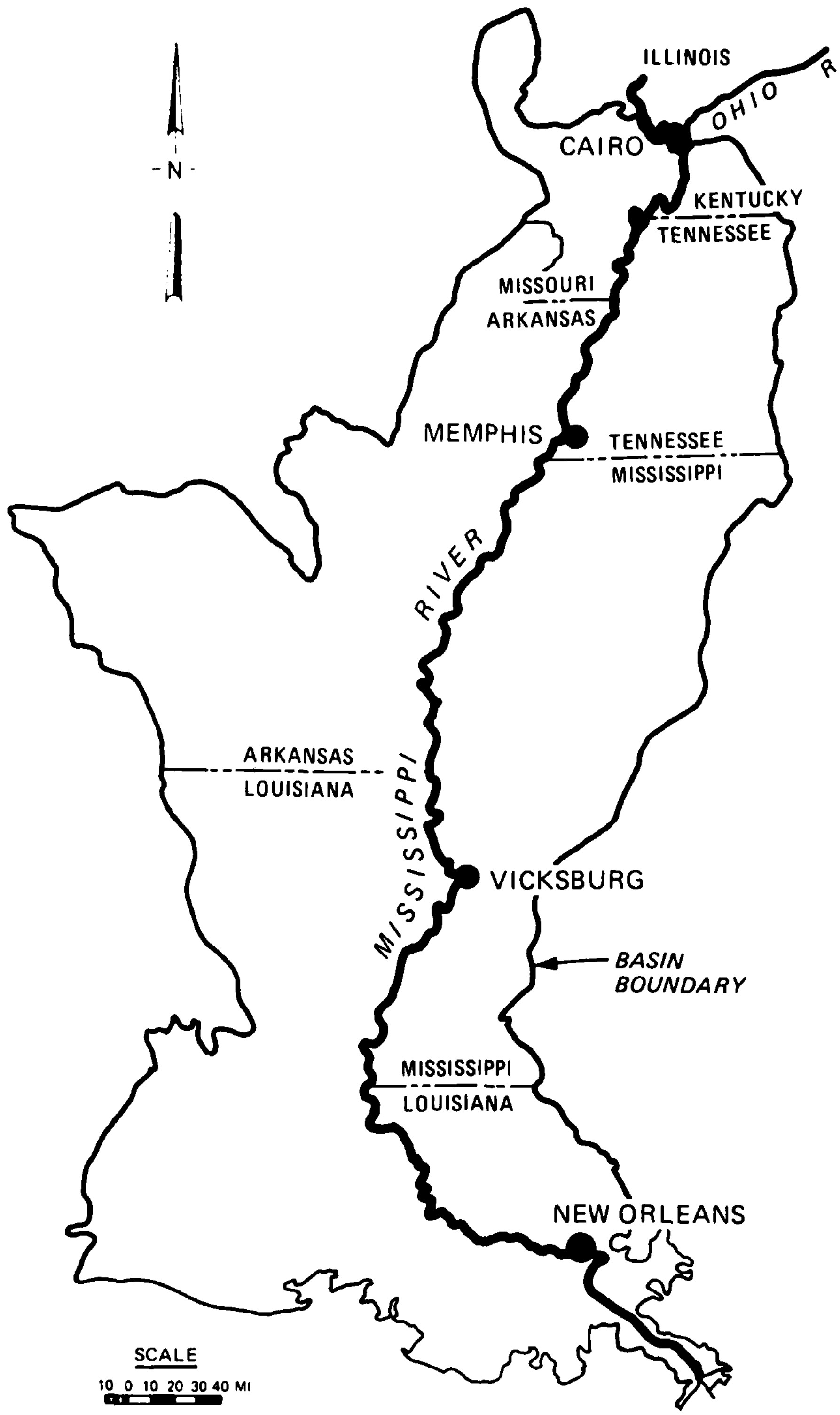

Figure A6. Lower Mississippi River basin

common. Streambank erosion occurs at a rate of 2-20 ft per year (ASCE 1965).

Ecological resources

76. Aquatic habitat. The interaction of the dynamic fluvial system of the lower Mississippi River with engineering structures has resulted in formation of new habitat types in addition to naturally occurring aquatic habitats. Cobb and Clark (1981) classified habitats along the lower Mississippi as main channel, secondary channel, natural sandbar, natural banks, revetted banks, dike fields, abandoned river channel, oxbow lake, borrow pit, and inundated floodplain.

77. Fishery. The lower Mississippi supports a diverse fishery. Common species include freshwater drum, flathead catfish, carp, gizzard shad, blue catfish, freshwater drum, and channel catfish (Pennington et al. 1980). Fish species in the lower Mississippi are adapted to conditions of moderate velocity and high suspended solids concentration.

78. Terrestrial habitat. Land use within the lower Mississippi Valley is primarily agricultural. Implementation of flood protection plans, e.g., levees and floodways, has encouraged agricultural development of most floodplain lands up to the landside of the levees. In many parts of the valley, riparian habitat is confined to the land between the levee and the channel, i.e., the portion of the floodplain periodically inundated by flood flows. Channel and bank stabilization structures have eased access to the channel for wildlife. Vegetation is not routinely cleared from revetments, and they support sparse growths of willows and herbaceous plants.

Institutional factors

79. Bank stabilization has been included as an integral part of channel improvement and stabilization for navigation and flood control purposes under the Flood Control Acts of 1928, 1944, and 1965. Bank stabilization has been authorized for 780 miles of the main stem of the lower Mississippi (Moore 1972). Revetments are constructed and maintained by the CE.

Streambank protection

80. A number of types of streambank protection have been tried

along the lower Mississippi, but articulated concrete mattresses (ACM) and riprap are used exclusively at the present time (Figure A7).

Figure A7. Articulated concrete mattress on the lower Mississippi

81. The ACM revetment is composed of concrete mattresses for lower bank protection and stone riprap for upper bank protection. Initially, asphalt paving was used for the upper bank, but now the upper bank is riprapped. The concrete mattresses are made up of 4- by 25-ft units consisting of 20 slabs, each 3 ft, 10.5 in. long, 14 in. wide, and 3 in. thick, spaced approximately 1 in. apart. The mattresses are cast at sites along the river and then assembled and placed from a floating plant (ASCE 1965).

82. Bank preparation is accomplished by grading the bank to a stable slope, usually 1V:3H, and placing a 4-in. gravel blanket. Banks are graded from the top of the bank to between 15 and 20 ft below the surface of the water. The mattresses are then placed on the bank from the waterline at the time of construction out to a point slightly beyond the subaqueous bank.

Recent findings

83. Biological field studies have recently been completed which evaluate the impacts of dikes and revetments on fish, benthos, and water quality within a 50-mile reach of the lower Mississippi (Beckett et al. 1983; Pennington, Baker, and Bond 1983). The conclusions regarding revetments are discussed below.

84. Aquatic habitats. Placement of ACM results in stabilization of the bottom substrate and bank. The habitat value of revetted banks is affected by age of the revetment, sinuosity of the bank line, and type of revetment material. Newer revetments lacking sediment and vegetation have lower habitat value than older structures that have become extensively vegetated with willow and cottonwood trees and a variety of sedges, grasses, and shrubs. A sinuous bank has more variable velocities than a straight bank due to eddies and upstream flow. The fish community associated with ACM is very similar to that of a natural bank. The revetted and natural banks differ in percentage and composition of various species. The ACM habitat supports a higher percentage, by weight, of sport-commercial species. The sport-commercial species are generally larger and better able to stand the higher velocities of revetted banks (Pennington, Baker, and Bond 1983). Larval fish investigations showed similar species diversity and abundance of larval fish adjacent to natural and revetted banks (Schramm and Pennington 1981).

85. The impact of ACM on benthic organisms is greater than on the fishery. ACM revetment replaces the natural substrate with an artificial concrete substrate. Sediment deposition, primarily bed-load sand and gravel, is scoured and deposited on top of the revetment as discharge and velocities fluctuate. The distribution and composition of benthic species in Mississippi River habitats was shown to be a function of physical attributes of the river system, primarily current and substrate (Beckett et al. 1983). Although a method for quantitatively sampling benthic macroinvertebrates on and under the ACM was not available, field observations during the study indicated ACM is productive habitat for benthic macroinvertebrates. When ACMs were exposed at low water, remnants of benthic organisms, pelecypod shells, caddisfly cases,

and larval chironomid tubes were observed on and under ACM revetments. Numerous mayfly burrows were observed in underlying cohesive clay substrate where the revetment had buckled (Figure A8). The ACM revetment stabilizes the cohesive clay substrate, providing a unique habitat for burrowing mayflies. A number of these mayfly taxa show a definite substrate preference for firm clay sediment (Mathis et al. 1981).

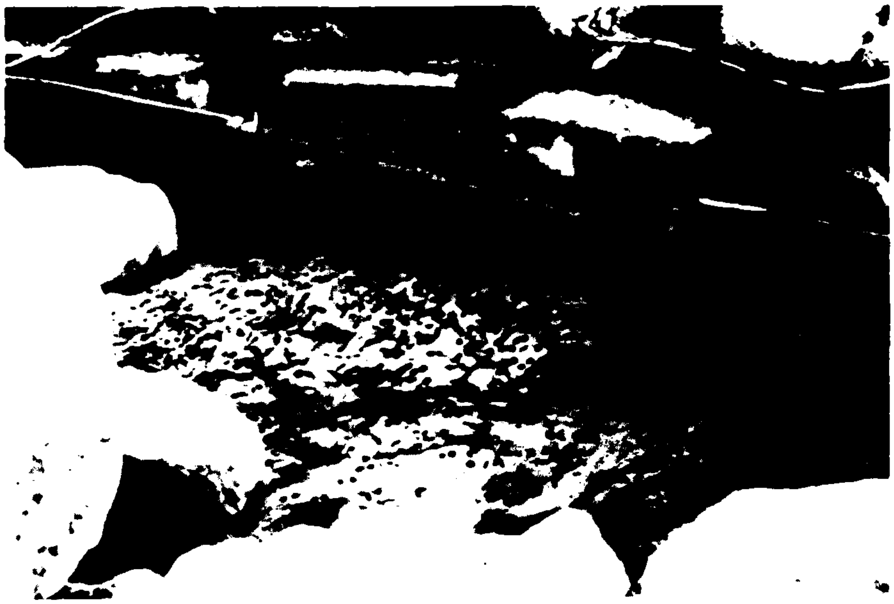

Figure A8. Mayfly burrows under ACM revetments

86. Terrestrial ecosystem. ACM revetment changes an eroding, often steep bank line habitat to a riprap or asphalt and mattress habitat. The prepared slope allows wildlife easier access to the river than does a steep, eroding natural bank. The habitat value for wildlife is dependent on factors cited above, i.e., vegetation on the revetment and the type of revetment material (Pennington, Baker, and Bond 1983).

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